THEORETICAL AND EXPERIMENTAL STUDY ON THE PROPAGATION OF HEAT INSIDE DEPOSITS OF COAL

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Summary

The phenomenon of self-ignition plays an important role in the design of coal storage piles. This paper presents a theoretical and experimental study on the propagation of heat inside coal deposits and consideration on the mechanism of spontaneous oxidation of coal at a low temperature.

1. Introduction

One of the principal problems in the design and management of large coal deposits concerns a possible deterioration in the quality of the coal due to the presence of oxygen in the atmosphere.

In effect, oxygen causes a slow but progressive oxidation of coal, starting on the external layers, thus resulting not only in a financial loss but also in a risk of fire through autocombustion.

Therefore, it is essential that the heat developed by spontaneous oxidation should be completely dissipated in order to avoid a gradual increase in temperature which could cause autocombustion.

The efficient dissipation of heat depends mainly on the criteria adopted during the construction of the pile. These criteria are all the more important as the dimensions of the pile increase [1].

The development of heat per unit volume of stocked coal depends mainly on the dimensions of the coal particle, the degree of compaction and its active characteristics.

In this work a theoretical model is presented, validated by experiments, for the forecasting of heat diffusion values inside coal piles related to the apparent stocking density.

The work also presents preliminary results concerning possible coal oxidation phenomena at low temperatures.

2. Approach to the problem

The point of this study is to establish by calculation if the sudden development of heat through autocombustion can be judged as being restricted to a limited proportion of the pile or whether there is a risk of the phenomenon extending rapidly to other parts of the pile.

As it is well known, transients for heat propagation are established by solving Fourier's general equation

$$\nabla^2 T = \frac{1}{\alpha} \frac{\partial T}{\partial \theta}. \tag{1}$$

In this particular case, where the heat was provided at the bottom of the pile, heat propagation can be considered as monodimensional, assuming a step change of temperature imposed on a semi-infinite wall with uniform initial temperature.

This is the equivalent of solving the following equation:

$$\frac{\partial^2 T}{\partial X^2} = \frac{1}{\alpha} \frac{\partial T}{\partial \theta}, \tag{2}$$

with these boundary conditions

$$\begin{cases} X > 0, & \theta = 0: & T = T_a \\ X = 0, & \theta > 0: & T = T_w \\ X \to \infty, & \theta > 0: & T \to T_a \end{cases} \tag{3}$$

A solution of eqn. (2) which satisfies the boundary conditions (3) is the well known complementary equation of Gauss' error curve [2]

$$\frac{T(X,\theta) - T_a}{T_w - T_a} = \text{erfc} \frac{X}{2\sqrt{\alpha\theta}}, \tag{4}$$

Since the coal pile is not a continuous body, in order to take into account the void volume inside the coal pile, we apply the effective thermal diffusivity α_e.

For the two-phase system (solid/gas), α_e can be defined by the equation

$$\alpha_e = \frac{K_e}{\rho_e C_e} = \frac{K_e}{\rho C(1-\varepsilon) + \rho_g C_g \varepsilon}, \tag{5}$$

where the K_e, the effective thermal conductivity, is calculated from [3] as

$$K_e = K \frac{1 - (1 - aK_g/K)\,\varepsilon}{1 + (a-1)\varepsilon}, \tag{6}$$

where $a = \dfrac{3K}{2K + K_g}$,

and it can be applied to two-phase systems.

In the case of a solid/gas system $K \gg K_g$, the equation for K_e becomes

$$K_e = K \frac{(1-\varepsilon)}{1+\varepsilon/2} . \tag{7}$$

Inserting (7) into (5), and combining the result with eqn. (4), we obtain the following final equation

$$\frac{T(X,\theta) - T_a}{T_w - T_a} = \mathrm{erfc} \frac{X}{\sqrt{\dfrac{K(1-\varepsilon)\,\theta}{(1+\varepsilon/2)\,(\rho C(1-\varepsilon) + \rho_g C_g \varepsilon)}}} , \tag{8}$$

which enables us to calculate the trend of theoretical temperature/time curves for a given distance X from the hot zone of the pile, and for coal piles with different degrees of compaction (porosity).

3. Results of the experiments

The experimental tests were carried out on a number of small piles of a standard shape, prepared with the same quantities of coal (0.5 kg), in suitable moulds having different volumes. So, piles were obtained with different degrees of compaction [4].

Each pile was subjected to controlled progressive heating by means of a thermostatic electric plate. The measurement and recording of temperatures were carried out using six iron–constantan thermocouples placed inside the pile at the same depth, along its longitudinal axis, and connected to a six-trace pen recorder.

3.1 Model validation

In a preliminary series of tests, the samples of coal were subjected to heating tests in inert atmosphere (nitrogen).

The sample pile was prepared in an airtight steel container having a volume of 5000 cc, complete with a hermetically-sealing lid of pyrex or steel.

The conditions for the tests were:
T_a = container ambient temperature = 60 °C,
T_w = electric plate temperature = 110 °C,
ρ_α = pile apparent density = 1100 kg/m^3.

The results obtained are depicted in Fig. 1, which also shows the theoretical trend calculated using eqn. (8).

It can be seen that the theoretical curve has a trend very similar to the curve resulting from the tests. This confirms the validity of the original assumptions on which the theoretical model was based.
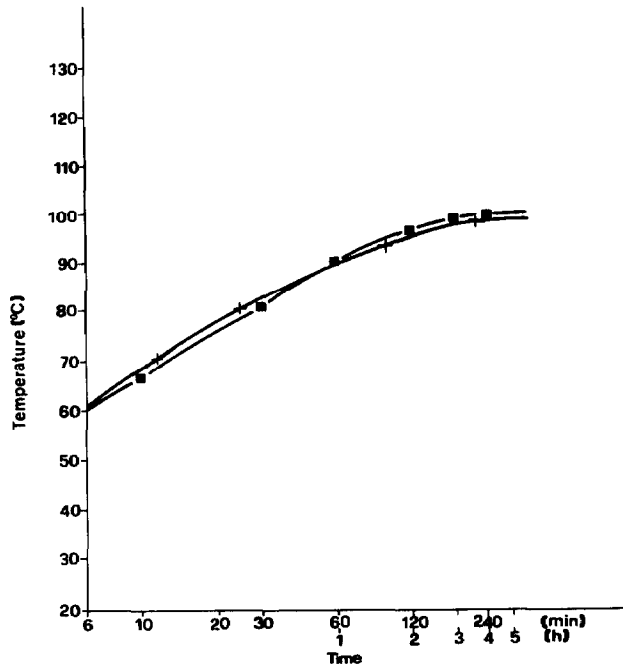
Fig. 1. Heating tests in inert atmosphere, comparison between experimental results and theoretical model. ■ experimental results, +theoretical model.

3.2 The heating of coal in air

Having checked the validity of the model in inert atmosphere, similar tests were carried out in the open air in order to see if the theoretical model could also apply to coal piles exposed to oxidation.

Therefore, in a second series of experimental tests, standard piles of coal in the open air were heated by means of a thermostatically controlled electric heating plate regulated to reach a temperature T_w of 130°C.

The tests, carried out on moisture free coal and in piles having various apparent densities, varying from 700 to 1100 kg/m^3, give the experimental temperature/time curves shown in Fig. 2.

Examination of the curves shows that coal piles with greater compaction (smaller porosity) reach the temperature T_w more quickly (i.e. in a shorter time).

In the same Fig. 2, theoretical curves based on the same conditions as established for the open air tests are shown.

As can be seen, there is a discrepancy between the measured and theoretical temperatures; the first are constantly higher.

From this it could be deduced that a distributed exothermic reaction develops with a subsequent heating of the coal at relatively low temperatures. In
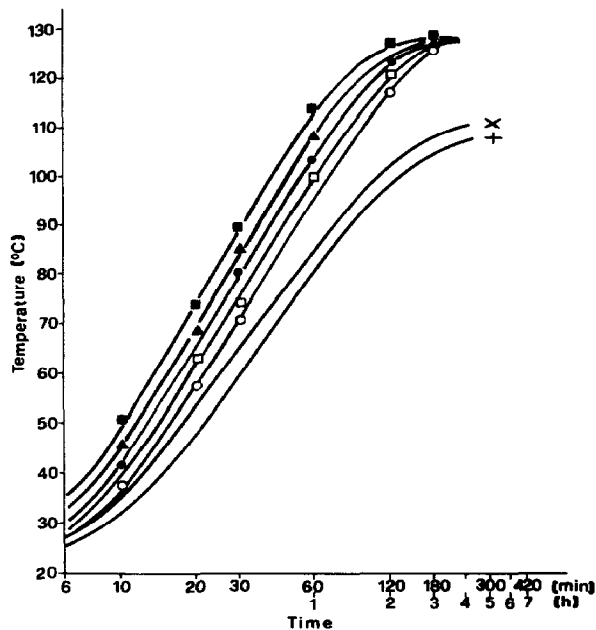
Fig. 2. Heating tests in air, comparison between experimental results and theoretical model. ○ experimental results, coal apparent density = 700 kg/m³, ☐ experimental results, coal apparent density = 800 kg/m³, ● experimental results, coal apparent density = 900 kg/m³, ▲ experimental results, coal apparent density = 1000 kg/m³, ■ experimental results, coal apparent density = 1100 kg/m³, + theoretical model, coal apparent density = 700 kg/m³, and × theoretical model, coal apparent density = 1100 kg/m³.

fact the difference between the theoretical curve and the experimental one tends to increase at higher temperatures; this shows that there is an accelerated increase of the temperature caused by the increase in the exotermic reaction rate which takes place at oxidation.

Experimental data gathered in this work seem to support an homogeneous exothermic reaction taking place inside the pile mass.

3.3 The phenomenon of coal oxidization at low temperature

In order to confirm the assumptions presented in Section 3.2, several sample piles were subjected to controlled heating tests in a closed environment (air-tight steel container with air) to establish the development of this process of oxidation by means of the variations in the composition of the air inside the container.

Continuous readings were made of the temperatures and simultaneously samples of the internal air were analyzed by gas-chromatography.

The test of each pile lasted 336 consecutive hours at a temperature of either 75°C or 100°C by means of an electric plate.
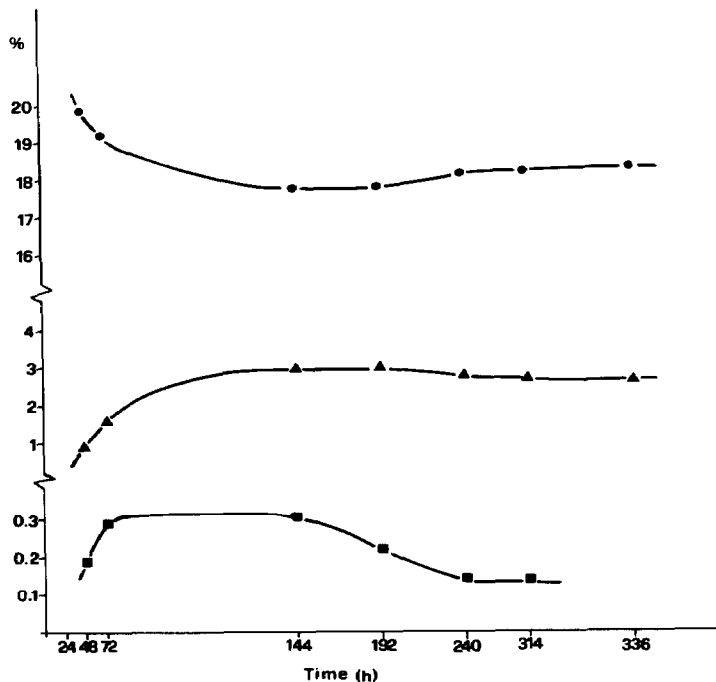
Fig. 3. Long period heating tests: $T = 75\,°C$ for 336 h; gas chromatographic analysis results for dry gases produced inside the closed environment, ● O_2, ▲ CO_2, ■ CO.
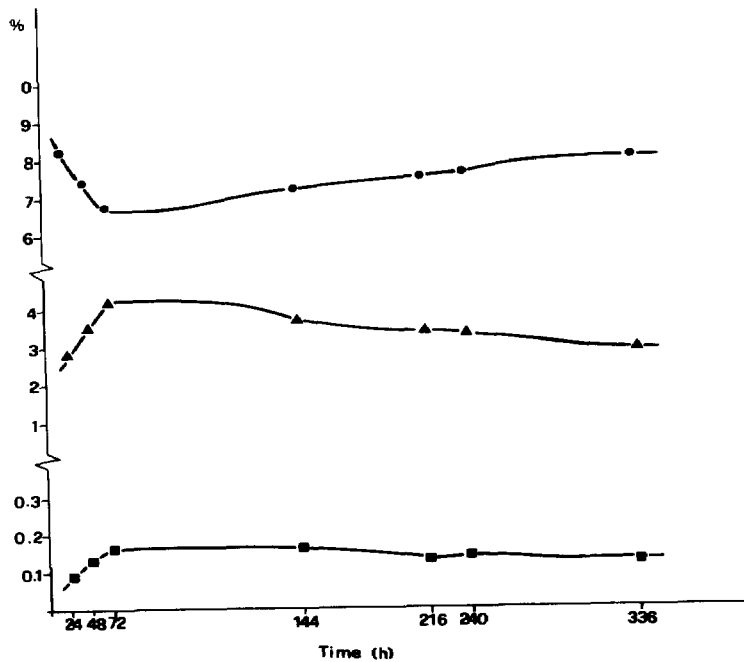

Fig. 4. Long period heating tests: $T = 100\,°C$ for 336 h; gas chromatographic analysis results for dry gases produced inside the closed environment. ● O_2, ▲ CO_2, ■ CO.

Preliminary results, shown in Figs. 3 and 4, match the theoretical forecast, which predicts, for the global process of coal oxidation, a step by step development. The first step, at low temperature, is the absorption of oxygen by the coal which brings about the formation of peroxide complexes. This absorption generates heat which is responsible for the heating of the coal itself. The peroxide complexes, being unstable, release CO and CO_2, while the increase in temperature (70–100°C) causes a process of oxygen desorption [5–7]. The last phenomenon is reported in Figs. 3 and 4 where an increase in the concentration of oxygen in the air is shown.

Further tests are being carried out in order to study the mechanism of the reaction at low temperature of coal to oxygen in the atmosphere and, at the same time, validate a kinetic oxidation model.

4. Conclusion

Spontaneous oxidation at low temperature inside coal piles and the subsequent start of a heating process, constitutes a risk which is always present where coal is stocked in the open air.

The most important consequences are a loss in terms of money due to a loss in the quality of the coal and damage to the environment due to emissions of pollutant gases.

In this work we have tried to present a forecast model for the trend in the variation and propagation of the temperature inside a coal pile subjected to a spontaneous or accidental generation of heat.

The results show that when providing heat by a distributed hot source (spontaneous or accidental) the propagation of heat in the various layers of a coal pile is accompanied by an exothermic oxidation reaction which starts even at low temperature, and causes a thermal increase trend greater than the theoretical one which is based only on the phenomenon of heat transport by thermal propagation.

Notation

a	dimensionless parameter (see eqn. 6)
C	specific heat (J/kgK)
C_g	specific heat of gaseous phase (J/kgK)
K	thermal conductivity (J/msK)
K_e	effective thermal conductivity (J/msK)
K_g	thermal conductivity of gaseous phase (J/msK)
T	temperature (K)
T_a	initial temperature (K)
T_w	hot wall temperature

X Distance from hot wall (m)

Greek letters

α thermal diffusivity (m^2/s)

α_e effective thermal diffusivity (m^2/s)

ε void fraction, dimensionless

θ time (s)

ρ density (kg/m^3)

ρ_g density of gaseous phase (kg/m^3)

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