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The accidental ignition of stockpiled low-rank coal by proximity to active combustion

J.C. Jones [1]

Department of Engineering, Fraser Noble Building, King's College, University of Aberdeen, Aberdeen AB9 2UE, UK

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Abstract

Previously presented kinetic parameters for the oxidation of a low-rank coal are used to predict hazards in situations where such a coal is stockpiled sufficiently close to combustion plant for there to be a possibility that a hot particle will be ejected into the storage area.

Keywords: Accidental ignition; Coal; Kinetic paramater; Storage

1. Introduction

A previous paper [1] presented activation energies E of ignition and thermal diffusivities α for a variety of brown coals (lignites) from different parts of the world. The activation energies were obtained by oven heating and application of the Frank–Kamenetskii model of thermal ignition, and thermal diffusivities were derived from heating and cooling curves. These quantities are relevant to spontaneous heating, as was pointed out in the earlier paper. However, they are also input to predictive calculations of ignition by a heat source, and this aspect is developed in the present paper.

We focus on the Victorian sample discussed earlier [1], which was a run-of-mine coal from the Latrobe Valley, Victoria, Australia, which had been crushed to a particle size range of 4–12 mm and air dried (not oven dried) before use in the experiments. For this, $E = 94$ kJ mol^{-1} [1], and for the purposes of the thermal calculation set out below we also need the pre-exponential factor A. This is calculated for the Victorian coal in Appendix A.

[1] Telephone 01224-272793; Fax 01224-272497.

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A point requiring comment is that, whereas the calculations are concerned with ignition by a heat source, the kinetic information was obtained in experiments in which ignition was "spontaneous" in the sense that it occurred without introduced heat. However, measured values of Arrhenius parameters—activation energy E and pre-exponential factor A—for the oxidation of combustible substrates are equally applicable to spontaneous and piloted ignition. The only conceptual difference is that the departure of the internal temperature profile from being flat is due to the material's own self-heating in the spontaneous case and to the introduced heat in the piloted case.

2. Theory and numerical calculation

2.1. An ejected coal particle: a simplified treatment

Let us imagine that combustion of the Victorian coal is taking place and that further fuel is stockpiled nearby. There is accidental ejection of a burning particle from the combustion plant with sufficient momentum for it to travel to the stockpile and become embedded in it. We envisage a particle at dull red heat, i.e., at ≈ 700°C, cooling to 500°C along its trajectory to the stockpile, giving a particle temperature T_i on entry of 773 K. We shall make use of "hot spot" theory [3,4] to predict how large the ejected particle will need to be in order to ignite the stockpile.

We utilise the dimensionless temperature Θ_i, given by

$$\Theta_i = \frac{E}{RT_i^2}(T_i - T_a) \tag{1}$$

where T_a is the ambient temperature, taken to be 298 K, and R is the gas constant (8.314 J K^{-1} mol^{-1}).

We also require the dimensionless heat-release rate δ

$$\delta = \frac{r_0^2 q\sigma AE\exp(-E/RT_i)}{kRT_i^2} \tag{2}$$

where k is the thermal conductivity of the coal [2] (W m^{-1} K^{-1}), δ_{crit} is the critical value of the Frank–Kamenetskii parameter, q is the exothermicity (J kg^{-1}) and r_0 is the dimension of the hot spot. Here, δ for the piloted ignition case differs from that used in the previous paper, and in Appendix A, in having T_i instead of T_o in the argument of the exponential and in the denominator. As in Appendix A, we make the substitution

$$k/\sigma = \alpha c \tag{3}$$

[2] A room temperature value of k for the hot spot is considered adequate in this calculation, in view of the fact that the final result for the critical value of r_0 is obtained to one significant figure only and that, in effect, $\sqrt{k}$ is used to calculate this critical radius. We re-examine the question of particle thermal conductivity in a subsequent section.

which follows from the definition of α. Substituting E, T_i etc. in Eq. (1) gives

$$\Theta_i = 9.0 \tag{4}$$

Now expressions for the critical condition for ignition by a reactive (as in this case) hot spot are of the form

$$\delta_{crit} = f(\Theta_i) \tag{5}$$

where δ is formulated according to Eq. (2), above. Thomas [3] obtained the expression

$$\delta_{crit} = 2\Theta_i \tag{6}$$

The Thomas expression is obtained on the basis that the heat generation in the hot spot due to reaction obeys a simple Arrhenius expression with respect to temperature (valid for brown coals, as the earlier spontaneous heating work demonstrated [1]) and that there is a distributed, not a flat, temperature profile within the particle with T_i the initial value of the temperature at the centre.

On this basis, in order to find the minimum size of particle at 773 K necessary for ignition of the stockpile, we combine Eq. (2), Eq. (3) and Eq. (6) and rearrange to give

$$r_o^2 = \frac{2\Theta_i \alpha c R T_i^2 \exp(E/RT_i)}{qAE} \tag{7}$$

Substituting, using the values of q and c given in Appendix A, the value of A calculated in the Appendix and the values of E and T_i above

$$r_o = 0.15\,\text{mm}$$

That is, an ejected hot coal fragment at 773 K stockpile entry temperature would need to be 0.3 mm or greater in diameter to ignite the stockpile. A smaller particle at the same temperature would fail to ignite it.

2.2. *An ejected coal particle: an alternative treatment*

Implicit in the treament above is the assumption that the coal particle has the same thermal conductivity as the bed into which it is ejected. This thermal conductivity k of the bed is simply $\alpha k \sigma = 0.07$ W m^{-1} K^{-1}. There are possible grounds for improvement on this treatment, not only because the particle thermal conductivity will differ from the bed value, but also because the coal particle will, having been ejected at dull red heat, have undergone extensive devolatilisation and hence composition change. A coke or char particle might well have a thermal conductivity very significantly higher than that of the coal bed, depending on the degree of voidage in the particle. Kern [5] gives k values for partially devolatilised higher rank coal particles of the order of 5 W m^{-1} K^{-1}.

Without using a precise numerical value for the hot particle thermal conductivity, or departing from the assumption of common thermal conductivity of hot spot and surrounding medium, it is possible to examine this point in the following way. Whereas a particle having a very low thermal conductivity, such as was considered above, will

have a steep radial temperature gradient, a particle with a significantly higher thermal conductivity will have a gentler gradient. The limiting case is where the thermal conductivity is sufficiently high for the profile at any time to be flat, with a temperature step at the boundary between the hot spot and the surrounding medium.

The critical condition for ignition by such a hot spot was developed by Boddington [6]. Boddington uses an initial temperature profile which is horizontal at T_i, which develops into a profile with a single average temperature T. δ_{crit} in his model is the lowest value for which the temperature of the hot spot rises after an initial drop. Rearrangement of the critical condition derived by Boddington for a spherical hot spot gives

$$\delta_{crit} = \Theta_i^2 \times \frac{9}{2\pi} \tag{8}$$

where δ and Θ_i are as defined in Eq. (2) and Eq. (1) respectively. Substituting our value of 9.0 for Θ_i for the Victorian coal, based on a hot spot entry temperature of 773 K

$$\delta_{crit} = 116 \tag{9}$$

giving, by combining Eq. (1) and Eq. (2) and rearranging

$$r_o = 0.4\,\text{mm}$$

a critical diameter of 0.8 mm, not hugely different from the earlier result. Note that neither in the original formulation by Boddington [6] nor in the above application is a value of infinity for the common "k" value assumed. The merit of the Boddington approach in this practical example is that it arbitrarily uses a single hot spot temperature —in effect the horizontal temperature profile—within the hot spot, which may be more appropriate than a model using a distributed temperature profile. Moreover, a profile approximating to flatness may be the result not only of a moderately high k but also of a small particle size.

2.3. An ejected char particle

In the present applications of the various hot spot formalisms there is the complication of devolatilisation of the hot spot before stockpile entry, and consequent differences in reactivity of the hot spot and the surrounding material. A hot spot at red heat will certainly have undergone a considerable degree of devolatilisation, and we can take the limiting case of a particle totally devolatilised and also rendered quite unreactive by the high temperature carbonisation. We can approximate such a particle to an inert hot spot at 773 K with the same physical characteristics (k, σ, c) as the unburnt coal which it subsequently contacts. The simple criticality condition applying (Zinn, [7]) is

$$\delta_{crit} = 25 \tag{10}$$

with δ defined as previously. The physical basis of Zinn's criterion is that there is an initial period during which, because of the thermal inertia of the surrounding medium,

the hot spot temperature remains at or close to its initial value. Equating this to the induction time of ignition, expressible in terms of δ, gives Eq. (10).

Substituting to obtain r_o, with the values of the quantities for the stockpiled material previously given

$$r_o = 0.2\,\text{mm}$$

This is very similar indeed to the results from the previous calculations, and before discussing the collective significance of the the numerical results for the ejected coal particle we will perform related calculations for mineral particles.

2.4. Ejected mineral particles

There are a number of ways in which particles of mineral composition might be present in the combustion, therefore it is potentially useful to repeat the above "hot spot" calculation for such a particle. The most obvious mineral particle would be ash, but there are two other possible sources. Fluidised bed combustion (FBC) of Victorian brown coal uses sand particles [8], and in FBC such particles, of diameter typically around 1 mm, can be elutriated from the top of the bed. The particular coal used in the experimental work from which the E and A values etc. were obtained is low in sulphur, but otherwise similar low-rank coals, from Victoria and elsewhere, can contain much more sulphur and might therefore be burnt with calcium carbonate or some other sulphur-fixing inorganic substance [4]. A mineral particle will of course constitute an inert hot spot of quite different k, c and σ values from those of the coal or char particles considered so far.

We shall use a treatment of ignition by Gol'dshleger et al. [9] according to which the critical condition is signalled by

$$\sqrt{\delta^*_{\text{crit}}} = 0.4\sqrt{b^2 + 0.25j(j+1)(b+0.1b^3)}\,[\Theta_i + 2.25(j-1)]^2[1 + 0.5\epsilon\Theta_i] \tag{11}$$

$$\sqrt{\delta_{\text{crit}}} = \sqrt{\delta^*_{\text{crit}}}\left[1 + \frac{(\Theta_i - 3)^2 b(j+1)}{30k_r^{2/3}(1+3b^{2/3})}\right] \tag{12}$$

where δ is as defined in Eq. (2), also

$$b = \frac{(\text{heat capacity} \times \text{density})_{\text{reacting medium}}}{(\text{heat capacity} \times \text{density})_{\text{hot spot}}} \tag{14}$$

$$k_r = \frac{\text{thermal conductivity of the hot spot material}}{\text{thermal conductivity of the reacting material}} \tag{15}$$

$$\epsilon = \frac{RT_i}{E} \tag{16}$$

and j is a factor whose value depends on the shape of the hot spot.

The Gol'dshleger et al. equations, above, were derived in the following way. Heat balance equations for hot spot and reacting medium were formulated and across specified parameter space temperature time trajectories were obtained by numerical integration. These enabled an ignition limit to be plotted which was fitted by Eq. (11) and Eq. (12). In applying the equations to our case of a hot particle entering a coal stockpile, we shall need to ensure that the parameters are within the ranges specified for the treatment. Let us continue to use a value of 773 K for the particle temperature on entry, in which case, as before in Eq. (4)

$$\Theta_i = 9.0$$

which is within the range 7.5–25 for which the approach is applicable [9]. We shall retain the values of the quantities for the coal and make use of the following approximate values for a sand particle at 773 K [10]

1. Thermal conductivity $= 2\ \mathrm{W\ m^{-1}\ K^{-1}}$
2. Density $= 2000\ \mathrm{kg\ m^{-3}}$
3. Heat capacity $= 1000\ \mathrm{J\ kg^{-1}\ K^{-1}}$

Also, $j = 2$ for a spherical hot spot [9], in which case r_o is the sphere radius.

Substitution gives

$$b = 0.31$$

$$k_r = 28.6$$

$$\epsilon = 0.07$$

and these are all within the ranges recommended [9] for use with Eq. (11) and Eq. (12).

With these values of Θ_i and the parameters, the contents of the square brackets in Eq. (12) have a value of 1.02, therefore

$$\sqrt{\delta_{crit}} = 1.05\sqrt{\delta^*_{crit}} \tag{17}$$

Substituting b, j, ϵ and Θ_i into the critical condition gives

$$\sqrt{\delta_{crit}} = 52.5$$

$$\delta_{crit} = 2756$$

We can rearrange Eq. (2) and substitute values of E, A etc. to give, to one significant figure

$$r_o = 2\,\mathrm{mm}$$

that is, a spherical particle of sand at 773 K would need to be 4 mm in diameter in order to ignite the coal stockpile in which it had become embedded. This is an order of magnitude higher than the results for the reactive hot spot, and that the latter requires smaller sizes to ignite the stockpile is intuitively logical.

Recalling that aluminium oxide is a mineral component of coals, especially coals with a significant clay content, let us perform an equivalent calculation for a hot spot composed of Al_2O_3 (also, of course, inert) at 773 K. For this [10]

1. Thermal conductivity $= 12.5\ \mathrm{W\ m^{-1}\ K^{-1}}$
2. Density $= 3900\ \mathrm{kg\ m^{-3}}$

3. Heat capacity $= 1150\ \mathrm{J\ kg^{-1}\ K^{-1}}$
   Substituting gives *

$$b = 0.14$$

$$k_r = 179$$

which are within the required range. Substituting further gives

$$\sqrt{\delta_{crit}} = 32.4$$

$$\delta_{crit} = 1049$$

$$r_o = 1\ \mathrm{mm}$$

therefore a 2 mm diameter particle of aluminium oxide at 773 K will ignite the stockpile.

3. Discussion and conclusions

Table 1 gives a summary of the numerical results. It is immediately apparent that, at 773 K, a mineral particle needs to be an order of magnitude larger than a coal particle to ignite the stockpile of coal. Each of the three models used to predict the behaviour of a partly burnt coal particle represents reasonably but without total accuracy the physical situation envisaged. Their collective message is that sub-millimetre particles at 773 K are an ignition hazard if allowed to enter the stockpile. Mineral particles of millimetre size at the same temperature pose the same hazard.

The above calculations have assumed sufficient penetration of the coal stockpile by the hot spot for the bulk properties of the former to apply. This will be so where the hot spot has considerable momentum and the stockpile has significant voidage. There is scope for further work in examination of a hot spot having penetrated only partially, so that coal particle rather than bulk stockpile properties will apply.

Table 1
Summary of the numerical results

	Physical basis	Critical diameter (mm)	Formalism applied
Calculation 1	Coal particle at 773 K entering the stockpile. A distributed temperature profile within the particle	0.3	Thomas [3]
Calculation 2	As for (1), but with a flat temperature profile within the particle	0.4	Boddington [6]
Calculation 3	A char particle at 773 K, unreactive and having the same k, σ and c values as the unburnt coal, entering the stockpile	0.4	Zinn [7]
Calculation 4	A sand particle at 773 K entering the stockpile	4	Gol'dshleger et al. [9]
Calculation 5	An alumina particle at 773 K entering the stockpile	2	Gol'dshleger et al. [9]

Appendix A

A.1. Calculation of A

The pre-exponential factor A is given by

$$A = \frac{k\delta_{crit}\exp[E/R(T_o)_{crit}] \times R(T_o)^2_{crit}}{\sigma r_o^2 qE} \quad \text{(A1)}$$

where δ_{crit} is the critical value of the Frank–Kamenetskii parameter; $(T_o)_{crit}$ is the critical ambient (oven) temperature (in K) for ignition of a cubic sample of half-side r_o (in m) and density σ (in kg m^{-3}); k is the thermal conductivity of the coal (W m^{-1} K^{-1}); q is the exothermicity (J kg^{-1}); and $k/\sigma = \alpha c$, where c is the heat capacity (J kg^{-1} K^{-1})

We have to select one $(T_o)_{crit}$, r_o data point to substitute into Eq. (A1), and that used is $(T_o)_{crit} = 400$ K for $r_o = 0.025$ m (i.e., a 5 cm cube) and sample density 536 kg m^{-3}. Other relevant quantities are

1. $\delta_{crit} = 2.57$
2. $\alpha = 1.13 \times 10^{-7}$ m^2 s^{-1} at this density [1]
3. $c = 1170$ J kg^{-1} K^{-1} [2]
4. $q = 20$ MJ kg^{-1}

Substituting, $A = 7 \times 10^5$ s^{-1}.

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