SPONTANEOUS COMBUSTION OF COAL

T. Myers[*] and B. Florio[†]

Industry Representative

Barend Erasmus[1]

Study group participants

A.G. Fareo, M.R.R. Kgatle, S.Mitchell, H. Sithole, S.P. Nchabeleng,
R. Mabasa, L. Borole, K. Born, S. Mungwe

Abstract

We investigate the phenomenon of spontaneous combustion in stockpiles of coal. That is, piles of coal left alone in the absence of any heat input may, over days or weeks, rise to a high enough temperature for combustion to occur. The internal heat is thought to be generated by slow surface reactions of the coal with atmospheric oxygen. If the generated heat is unable to escape quickly, then the internal temperature rises.

Spontaneous combustion is a huge problem in the coal industry, where the resource is often stored or transported in large piles, so understanding and preventing fires is important. There are many factors which may contribute to spontaneous combustion including: pile size, atmospheric moisture content, wind, coal type, internal heat and oxygen transfer, specific chemical kinetics, and stockpile geometry.

We analyse a series of continuum models of increasing complexity to explain spontaneous combustion. It is found that the pile size is a strong contributing factor. It is also shown that for accuracy of the model, the internal consumption and transport of oxygen must be taken into account.

These models will form a basis for future investigations using sophisticated models which could, for example, explore the influence of stockpile geometry.

[*]Centre de Recerca Matemàtica, Campus de Bellaterra, Edifici C, 08193 Bellaterra, Barcelona, Spain. *email: tmyers@crm.cat*

[†]Mathematics Department, University of Western Australia, Crawley, Australia *email: brendan.florio@uwa.edu.au*

[1]Global Change Institute, University of the Witwatersrand. *email: barend.erasmus@wits.ac.za*

1   Introduction

In the energy industry, it is quite common to keep coal in large piles for storage or transportation. Occasionally, the coal catches fire for no discernible reason which is obviously a tragic event for a pile of combustible fuel. As well as the monetary loss of coal stock, these fires can be catastrophic to the industrial infrastructure, pollute the local environment and endanger human lives. Spontaneous combustion during ship transportation is particularly dangerous.

Spontaneous combustion occurs not just in coal but in other piles of materials including hay, compost, manure and pistachio shells. We have even seen a similar problem in sugar cane bagasse at the 2017 Cape Town MISG [1].

There has been a wealth of literature in the past few decades explaining the spontaneous combustion of coal. It turns out that even at atmospheric temprerature, the coal reacts slowly with the oxygen in the environment releasing small amounts of heat in an exothermic reaction [2]. This is a problem for large pile of coal as the heat can accumulate, pushing the temperatures upward. If the coal becomes hot enough for combustion reactions to occur then this generally leads to catastrophic fires which we want to avoid.

At low temperatures ($< 70°$), the atmospheric oxygen attaches to the surface of the coal via adsorption reactions. These reactions tend to occur slowly and release a small amount of heat. Combustion reactions begin to occur between $70°$ and $130°$ [2]. Here, the carbon in coal reacts with atmospheric oxygen to produce carbon dioxide:

$$C + O_2 \rightarrow CO_2.$$
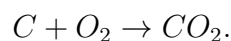
Once these reactions become significant enough to become self-sustaining, we could say that spontaneous combustion has begun. This two-reaction synopsis is a simplification, and further subclasses of reactions can be detailed [3].

While size of the coal pile seems to be the main contributing factor to the likelihood of spontaneous combustion, other factors include moisture level [2], wind speed and degree of shelter.

The main question brought to us by the industry representative was how the shape of the coal pile effects the likelihood of combustion. In industry, piles of coal can be arranged as inverted cones (or pyramids), in straight lines or in zig-zag lines (sometimes called chevrons). See figure 1 for a cartoon of these arrangements.

In Section 2, we begin by modelling a very simple one dimensional coal bed where heat is generated uniformly in time and space. This will provide us with a foundational base upon which we can better understand the problem before adding complexities. In Section 3, we consider the effect of temperature-dependent heat generation which is a common phenomenon in chemical reactions. Finally, in Section 4, we model the consumption and replenishment of atmospheric oxygen to better understand the spatial location of the oxidation reactions.
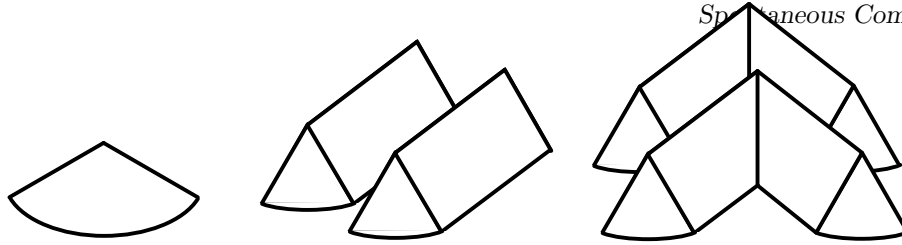
Figure 1: Possible storage shapes from left to right: Cone piles, straight line piles and chevron piles.
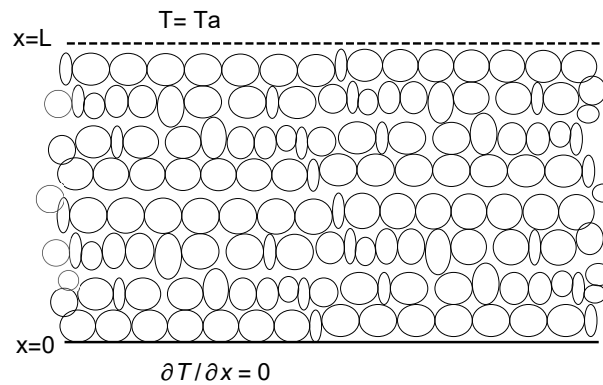
2   Uniform heating model

Figure 2: A cartoon of a coal bed, which would be modelled by a one-dimensional heat equation in the vertical coordinate, x.

We begin our modelling process by first restricting our attention to a simple one-dimensional coal bed (see Figure 2) to understand how the temperature changes in time. To model the generation of heat via the low temperature exothermic oxidation reactions we assume this occurs everywhere within the bed at a constant rate. Thus, the equation governing temperature in the bed is given by

$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} + q,$$

where T is the temperature, x is the height coordinate, t is time, ρ is the effective density of the coal pile, c the specific heat, k the thermal conductivity and q is the rate of heat generation per unit volume. Physically, q would be dependent on the rate of adsorption reactions and the individual heat generated. We can approximate the heat generated by an

Arrhenius term, such that

$$q = XHFe^{\frac{-E}{RT}}, \tag{1}$$

where X is the local concentration of oxygen, H is the enthalpy, F is the exponential pre-factor, E is the activation energy of the adsorption reaction, and R is the universal gas constant. Including oxygen and temperature dependence in the heat source term complicates the model so we make the simplification here that the reactions happen at the rate determined by the ambient temperature, T_a, and the coal pile is well oxygenated so the oxygen remains at concentration X_a. That is, we let $X = X_a$ and $T = T_a$ in equation (1). We relax these assumptions in later sections.

We consider the pile to have a height L, and the temperature at the upper surface to be the atmospheric temperature, T_a. The ground is taken to be insulating and the pile is initially assumed to be at atmospheric temperature. Thus, the boundary conditions are given by

$$T(L,t) = T_a, \qquad \left.\frac{\partial T}{\partial x}\right|_{x=0} = 0, \qquad T(x,0) = T_a.$$

To nondimensionalise the problem, we have a natural spatial scale in L, while the time and temperature scales need to be obtained. Thus we make the transformation

$$x' = \frac{x}{L}, \qquad t' = \frac{t}{\tau}, \qquad T' = \frac{T - T_a}{\Delta T}$$

To balance the terms and eliminate any dimensionless parameters, we define

$$\tau = \frac{L^2}{\kappa}, \qquad \Delta T = \frac{qL^2}{k}.$$

Dropping the prime notation, the dimensionless equation is given by

$$\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + 1, \tag{2}$$

subject to

$$T(1,t) = 0, \qquad \left.\frac{\partial T}{\partial x}\right|_{x=0} = 0, \qquad T(x,0) = 0. \tag{3}$$

As equation (2) has no dimensionless constants, we see that changing the value of the physical parameters will not change the behaviour of the system and will only change the temperature values. From the temperature scale, we also learn which physical parameters are important in determining the maximum temperature. We see that ΔT is proportional to L^2, meaning that the maximum temperature is strongly dependent on the height of the pile. This explains why pile size is a huge factor in spontaneous combustion. Increasing the heat input, q increases the maximum temperature for obvious reasons. A low thermal conductivity also increases the maximum temperature as the heat is trapped within the coal pile.

We can solve equation (2) analytically, which is one of the main advantages of the simplified model. We begin by separating the transient and steady state solutions such that

$$T(x,t) = U(x,t) + T_s(x).$$

As $t \to \infty$, the transient solution, $U(x,t)$, decays to zero leaving only the steady state solution, $T_s(x)$, which should satisfy the boundary conditions in its own right. Thus, the steady state problem is given by

$$\frac{\mathrm{d}^2 T_s}{\mathrm{d}x^2} = -1 \,, \qquad \left. \frac{\mathrm{d}T_s}{\mathrm{d}x} \right|_{x=0} = 0, \qquad T_s(1) = 0. \tag{4}$$

The steady state solution is then given by

$$T_s(x) = \frac{1}{2}(1 - x^2). \tag{5}$$

The transient problem is given by

$$\frac{\partial U}{\partial t} = \frac{\partial^2 U}{\partial x^2}, \qquad \left. \frac{\partial U}{\partial x} \right|_{x=0} = 0, \qquad U(1,t) = 0, \qquad U(x,0) = -T_s(x).$$

This eigenvalue problem can be solved by separation of variables, and the solution is given by

$$U(x,t) = \sum_{n=1}^{\infty} A_n e^{-\lambda_n^2 t} \cos(\lambda_n x),$$

where

$$\lambda_n = \frac{2n-1}{2}\pi, \qquad A_n = -2 \int_0^1 T_s(x) \cos(\lambda_n x) dx.$$

Convergence is quite fast for this series; even just using one term in U results in errors less than 5%. We take three terms to reduce the error below 1%. The full solution is shown in Figure 3 at various times.

The steady state solution (5) shows the maximum temperature that the coal pile will obtain after warming slowly by the low temperature oxidation reactions. We see here that the maximum temperature occurs at the bottom of the coal pile, at a dimensionless maximum temperature of $T = 1/2$. Thus we can determine that maximum dimensional temperature by redimensionalising. If we were to set a threshold temperature at which combustion occurs, T_c then we would say the coal pile is in danger if

$$T_a + \frac{qL^2}{2k} \geq T_c.$$

As a practical concern, the maximum height of a coal pile with no danger of combustion is given by

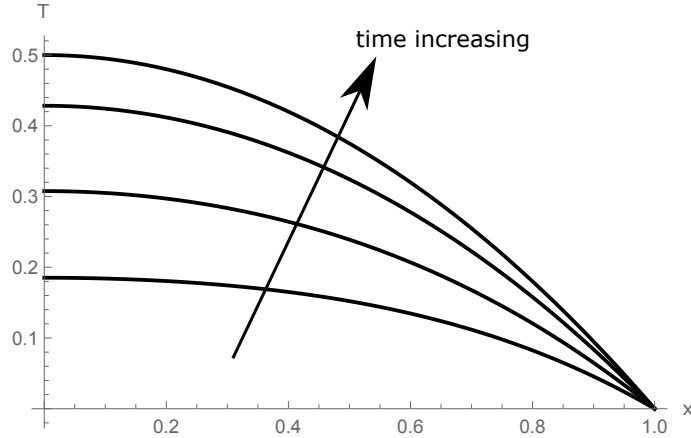$$L = \sqrt{\frac{2k}{q}(T_c - T_a)}.$$

Figure 3: The temperature within the bed increases as time passes. The profiles are shown for $t = 0.2, 0.4, 0.8$ and $t \to \infty$ (the steady-state solution).

	Symbol	value	units
coal density	ρ	1300	kg m^{-3}
coal specific heat	c	1003	J K^{-1} Kg^{-1}
coal thermal conductivity	k	0.2	W m^{-1} K^{-1}
ambient temperature	T_a	300	K
critical temperature	T_c	370	K
adsorption activation energy	E	4×10^4	J mol^{-1}
gas constant	R	8.31	J mol^{-1} K^{-1}
atmospheric oxygen concentration	X_a	9.4	mol m^{-3}
enthalpy	H	4×10^5	J mol^{-1}
exponential pre-factor	F	50	s^{-1}
diffusivity of oxygen in air	D	2×10^{-5}	m^2 s^{-1}
flow speed in porous medium	u	1×10^{-3}	m s^{-1}
heat transfer coefficient	h	5	W m^{-2} K^{-2}
mass transfer coefficient	h_X	1×10^{-3}	m s^{-1}

Table 1: Physical parameters and their values, taken from [2] and [3].

For bed heights above this value, there would be a very real danger of spontaneous combustion. Using the physical parameters from Table 1 (where we take $T_c \approx 100°$C), we find that the critical height is given by $L = 1.18$ m. This seems to be a little bit low given the industry experience, and so it is clear that our assumptions may be too harsh, and that we must extend the model.

3   Temperature-dependent reactions

Here we allow the Arrhenius term to be temperature-dependent such that the rate of oxidation is allowed to increase for larger temperatures. The dimensional heat equation then becomes

$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} + X_a H f e^{\frac{-E}{RT}}. \tag{6}$$

To obtain an analytical solution, we can modify the Arrhenius term by an approximation, by setting

$$\frac{1}{T} \approx \left(\frac{1}{T_c}\right)\left(2 - \frac{T}{T_c}\right),$$

to give

$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} + X_a H f e^{\frac{E}{RT_c}\left(\frac{T_a}{T_c} - 2\right)} e^{\frac{E \Delta T}{RT_c^2} T},$$

with the boundary conditions as in (3) above. To nondimensionalise, we repeat the procedure above with the exception of the temperature scale which we define as

$$\Delta T = \frac{L^2 X_a H f e^{\frac{E}{RT_c}\left(\frac{T_a}{T_c} - 2\right)}}{k}.$$

The dimensionless heat equation is thus given by

$$\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + e^{\mu T}, \tag{7}$$

subject to

$$T(1,t) = 0, \qquad \left.\frac{\partial T}{\partial x}\right|_{x=0} = 0, \qquad T(x,0) = 0,$$

where $\mu = E\Delta T/(RT_c^2)$. Myers *et al.* [4] found a similar equation in the context of temperature-dependent viscosity in fluid flow. Following their procedure, we can find the steady state solution, $T_s(x)$, by solving

$$\frac{d^2 T_s}{dx^2} = -e^{\mu T_s}.$$

Multiplying both sides by $\frac{dT_s}{dx}$ and integrating, we find that

$$\frac{dT_s}{dx} = \pm\sqrt{\frac{2}{\mu}\left(e^{\mu T_m} - e^{\mu T_s}\right)}, \tag{8}$$

where $T_m := T_s(0)$ is unknown but (8) satisfies the boundary condition (4) at $x = 0$. Now, as we expect the temperature to be the hottest at the centre, it is the negative branch of this solution which is physically viable. We can then further integrate to find the solution

$$T_s = \frac{1}{\mu} \log \left(e^{\mu T_m} \left[1 - \tanh \left((x - b)\sqrt{\frac{\mu e^{\mu T_m}}{2}} \right) \right] \right),$$

where b is chosen to satisfy the boundary condition (4) at $x = 1$:

$$b = 1 - \sqrt{\frac{2}{\mu e^{\mu T_m}}} \tanh^{-1} \left(\sqrt{1 - e^{-\mu T_m}} \right).$$

The temperature at the centre, T_m can then be found by using $T_m = T_s(0)$, which gives the implicit solution

$$T_m = \frac{1}{\mu} \log \left(e^{\mu T_m} \left[1 - \tanh \left(-b\sqrt{\frac{\mu e^{\mu T_m}}{2}} \right) \right] \right). \tag{9}$$

This equation is difficult to solve analytically, so we will resort to numerical methods. Using L as our bifurcation parameter, we find that for $L < 0.375$ m, there are two tangential roots to (9), indicating two possible steady state solutions. For $L > 0.375$ m, no roots are found. For example, for $L = 0.37$ m, the two roots are found; the lower at $T_m = 1.14$ and the upper at $T_m = 1.63$. Figure 4 shows a graph of $T_m - T_s(0)$ for subcritical and supercritical values of L. Decreasing L does not effect the location of the lower solution too much, but the upper solution can grow quite substantially

Without any serious analysis, we can infer the stability of these two solutions. We see from (7) that if the temperature is uniformly zero as per the initial condition, (3), then the conduction term is zero and the temperature grows in time toward the lower solution which appears to be stable. To facilitate the saddle-node bifurcation at $L = 0.375$ m, the upper solution must be unstable. For internal temperatures between the two solutions, heat is able to adequately escape from the coal bed and so temperatures return to the lower solution where the loss of heat equals the heat generated. Conversely, for temperatures above the upper solution, the Arrhenius term generates a significant amount of heat at a faster rate than the heat can escape. In this case, the temperature climbs indefinitely in a runaway process.

For $L > 0.375$ m, there are no stable solutions. The heat generated by the Arrhenius term is always greater than the heat escaping and runaway temperatures are inevitable, regardless of our initial conditions. Now we see that we have two conditions for which spontaneous combustion may occur; Either the stable-steady state solution exceeds our threshold temperature, or we have no stable solution and have runaway temperatures.

The dimensionless stable solution at the critical point, $L = 0.375$ m, is shown in Figure 5. For very low values of L, we find that the lower solution corresponds to $T_m \approx 0.5$. This
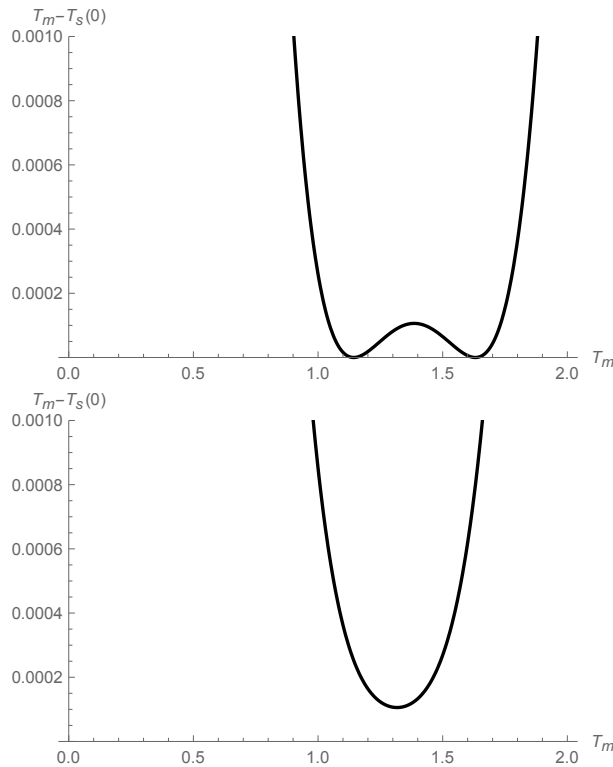
Figure 4: The subcritical ($L = 0.37$ m) and supercritical ($L = 0.376$ m) graphs of $T_m - T_s(0)$, respectively. The subcritical case has two roots, indicating two steady-state solutions, while the supercritical case has none.

makes complete sense because if $L \ll 1$, then $\mu \ll 1$ and the Arrhenius term in (7) becomes approximately equal to 1. This equation is then equivalent to the previous section where we found the dimensionless maximum temperature to be $1/2$. Our $T_m = 1.32$ at our critical point is the maximum stable temperature our system can reach. Dimensionally, this corresponds to $T = 60.3°$C. As this maximum temperature is below our threshold temperature of $100°$C for combustion we find that as long as we have a stable solution combustion will not occur. So we say that coal beds of a height greater than 37.5 cm will experience runaway temperatures and thus combustion.

Just like the previous section, the bed height for which combustion occurs appears to be a little bit low. While we have included temperature-dependent reaction rates, we still have not considered the consumption and transportation of oxygen and how this affects the problem.
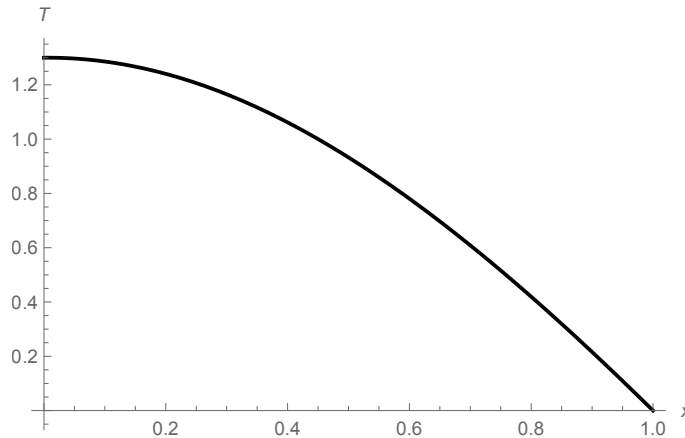
Figure 5: The steady state solution for $L = 0.375$ m. If we increase the bed height, no stable solution exists.

4 Coupled oxygen and temperature transport.

We now begin to incorporate other factors that effect the reaction rate, such as the local concentration of oxygen. Strictly speaking, the presence of water is required to catalyse the adsorption reaction. Paradoxically large amounts of water can also inhibit the reaction rate by providing a diffusion barrier to oxygen (see [5]). We are interested in modelling the worst-case scenario where the reaction rate is maximised, so we assume the presence of a thin layer of water and forego a detailed model of moisture transport.

The oxygen is consumed by the chemical reactions and must be replenished from the atmosphere. The heat equation remains similar to (6), however, the oxygen level is no longer constant and must be modelled by its own governing equation. The dimensional coupled system is given by

$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} + FHX e^{\frac{-E}{RT}}, \tag{10}$$

$$\frac{\partial X}{\partial t} + u \frac{\partial X}{\partial x} = D \frac{\partial^2 X}{\partial x^2} - FX e^{\frac{-E}{RT}}, \tag{11}$$

where $X(x,t)$ is the local oxygen concentration, u is the air flow speed through the porous medium, D is the diffusivity of oxygen in air. The oxygen model in essence describes how

the concentration of oxygen changes due to diffusion, advection and consumption by chemical reactions. The initial and boundary temperature condition are similar to the previous section, except here we use a Newton cooling condition at the top of the pile to allow greater flexibility. Thus we have

$$T(x,0) = T_a, \qquad \frac{\partial T}{\partial x}\bigg|_{x=0} = 0, \qquad k\frac{\partial T}{\partial x}\bigg|_{x=L} = -h(T - T_a),$$

where h is the heat transfer coefficient. Similarly, we assumed that the coal bed is initially well oxygenated and can be replenished via a "Newton cooling" type condition at the top of the bed:

$$X(x,0) = X_a, \qquad \frac{\partial X}{\partial x}\bigg|_{x=0} = 0, \qquad D\frac{\partial X}{\partial x}\bigg|_{x=L} = -h_X(X - X_a),$$

where h_X is the mass transfer coefficient. We then apply the following transformations to nondimensionalise the problem:

$$x' = \frac{x}{L}, \qquad t' = \frac{t}{\tau}, \qquad T' = \frac{T - T_a}{\Delta T}, \qquad X' = \frac{X}{X_a},$$

where

$$\tau = \frac{L^2}{\kappa}, \qquad \Delta T = \frac{FHX_aL^2e^{-\nu}}{k}, \qquad \nu = \frac{E}{RT_a}. \tag{12}$$

The dimensionless equations (dropping the primes) are then given by

$$\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + Xe^{\frac{\nu\alpha T}{1+\alpha T}}, \tag{13}$$

$$C_1\frac{\partial X}{\partial t} + \frac{\partial X}{\partial x} = C_2\frac{\partial^2 X}{\partial x^2} - C_3Xe^{\frac{\nu\alpha T}{1+\alpha T}}, \tag{14}$$

subject to initial and boundary conditions,

$$T(x,0) = 0, \qquad \frac{\partial T}{\partial x}\bigg|_{x=0} = 0, \qquad \frac{\partial T}{\partial x}\bigg|_{x=1} = -C_4T(1,t), \tag{15}$$

$$X(x,0) = 1, \qquad \frac{\partial X}{\partial x}\bigg|_{x=0} = 0, \qquad \frac{\partial X}{\partial x}\bigg|_{x=1} = -C_5(X(1,t) - 1). \tag{16}$$

The dimensionless parameters are given by

$$\alpha = \frac{\Delta T}{T_a}, \quad \nu = \frac{E}{RT_a}, \quad C_1 = \frac{L}{u\tau}, \quad C_2 = \frac{D}{uL}, \quad C_3 = \frac{FLe^{-\nu}}{u}, \quad C_4 = \frac{hL}{k}, \quad C_5 = \frac{h_XL}{D}.$$
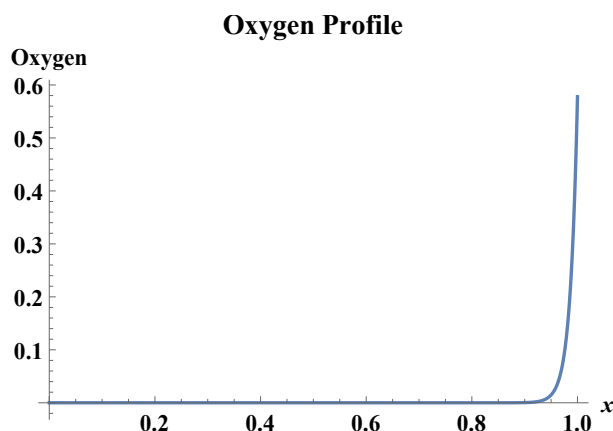
Figure 6: After a short amount of time, the internal oxygen is rapidly consumed, leaving a thin boundary layer at the surface.

This system of equations is then numerically solved for a sample set of parameters by using the method of lines. We find that the internal oxygen is rapidly consumed, leaving a small amount of usable oxygen in a thin layer near the surface of the bed. An example of the steady-state oxygen profile is shown in Figure 6.

This means that the oxidation reactions become spatially limited to the surface of the pile. This is indeed reflected in the temperature solutions (Figure 7), which show the transient temperature growing predominantly in this outer boundary layer. At steady-state, however, the internal temperature does plateau. This is due to the build up of heat conducted internally from the surface reactions and not due to internal reactions (which are not significant due to oxygen starvation).

In obtaining the results, we have assumed that the wind speed at the surface of the pile, u, is also the speed of the internal air of the pile. This assumption is again made to see the worst-case scenario of maximum oxygen supply. We see from Figure 7, however, that the majority of the oxygen is consumed at the surface of the pile. Thus the assumption of a constant internal u is not a bad approximation, as its value has little effect on the results.

The above results show how crucial it is to take oxygen dynamics into account for the modelling of coal bed self heating. Molecular diffusion of oxygen is small, so the replenishment of oxygen is largely driven by the airflow which would affect the u and h_X parameters. One conclusion we could make here is that to prevent a coal bed from combustion, we should deprive it of oxygen by keeping it well sheltered. This is indeed observed in practise [3], but
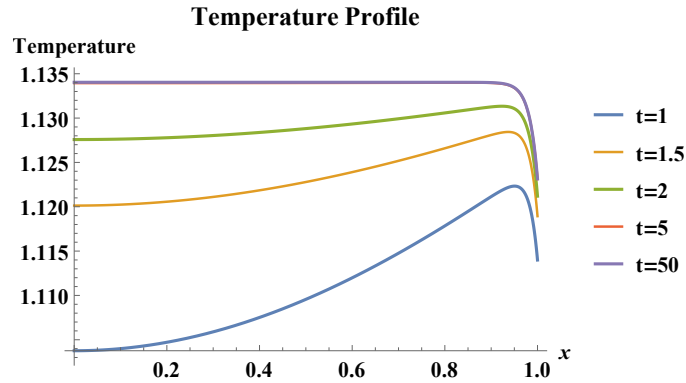
Figure 7: The temperature grows rapidly at the surface due to the local reactions there and eventually plateaus internally at steady-state.

there is another situation where combustion is rarely seen: High wind flow. This seems contradictory as here oxygen would be abundant, but a high wind flow also acts to cool down the coal pile [3]. From a modelling perspective, this would change our heat transfer coefficient, h, or perhaps cause us to add a heat advection term into (11).

4.1   A note on the effect of porosity

We have been assuming that the coal bed is a porous medium so strictly speaking we should be using appropriately homogenised parameters such as c_p, ρ_p and k_p in lieu of c, ρ and k. The usual thing to do is to take the arithmetic mean by defining

$$(\rho c)_p = (1 - \phi)(\rho c) + \phi(\rho c)_a \approx (1 - \phi)(\rho c),$$
$$k_p = (1 - \phi)k + \phi k_a \approx (1 - \phi)k,$$

where the "a" subscripts denote the properties of air, which are much smaller than their solid counterparts, allowing the approximation. These corrected parameters could then be used in the governing equations for a more accurate result.

In practise, the porous thermal conductivity, k_p, does not seem to obey this relationship. In fact, Rosema *et. al* [6] use a thermal conductivity model based on the experimental findings in soil of De Vries [7]:

$$k_p = \frac{s(1 - \phi)k + \phi k_a}{\phi + s(1 - \phi)},$$

where

$$s = \frac{0.66}{1 + 0.125\frac{k}{k_a}} + \frac{0.33}{1 + 0.75\frac{k}{k_a}}.$$

In this relationship, the thermal conductivity decreases more rapidly with porosity.

5   Discussion

Another aspect which requires more consideration is the "consumption" of coal which we have not taken into account unlike the depletion of oxygen, which we did model. As the oxidation reaction occurs on the surface of a coal lump, a protective surface layer forms preventing further reactions [2]. Thus we could model two states where reactive coal becomes unreactive after sufficient oxidation. Note that even if this surface layer does not form, there is still only a finite amount of reactive coal.

We can speculate on the results of such a model. Initially, the oxidation reactions will occur near the surface of the coal pile consuming oxygen in a familiar way. As the surface coal becomes less reactive, some sort of "reaction front" separating the two phases of coal will proceed into the depths of the pile. Oxygen will need to penetrate deeper into the pile as time goes on which acts to slow the reactions down. Another thing to consider is that there would be no high-temperature steady-state solution; once the coal is oxygen-saturated and no longer reactive, the temperature of the pile should drop back down to the atmospheric temperature. While the above models might suggest combustion temperatures are reached, if we were to include unreactive coal in the model, then we might find that we run out of fuel long before these temperatures are attained.

In this one-week study group we were able to model the coal combustion problem in one dimension. To address the question of how the shape and arrangement of coal piles affects the likelihood of combustion we really need to model a three-dimensional domain with non-trivial boundaries. Computational models can then be used to obtain detailed results. The one-dimensional models we used above can then be used to a) validate the accuracy of the computational models and b) inform us of what behaviour we expect so we can determine if the computational results are sensible.

6   Conclusion

The main question from the industrial representative was how the shape and arrangement of the coal piles affects its likelihood to spontaneously ignite. Unfortunately we were unable to address this directly but the models developed in this week will provide a strong foundation for more detailed modelling in follow-up work. From these models, we have a strong intuition of how the temperature and oxygen behaves under various circumstances. The major finding was that the pile size has a huge effect on combustibility. We can see clearly from these simple

models that the height of a coal pile has a huge effect on the likelihood of combustion. We have also seen that due to the faster reactions at high temperatures, there is a possibility of unstoppable runaway reactions. All precautions should be taken to avoid this.

References

[1] Myers T G and Mitchell S L. Safe storage of sugar cane bagasse. Proceedings of the Mathematics in Industry Study Group, South Africa, 2017, African Institute for Mathematical Sciences, Cape Town, editor DP Mason, pp 55-68..

[2] Brooks K S. A simplified model for spontaneous combustion in coal stockpiles. PhD thesis, University of the Witwatersrand, 1985.

[3] Zhang J, Ren T, Liang Y and Wan Z. A review on numerical solutions to self-heating of coal stockpile: Mechanism, theoretical basis and variable study. Fuel, 182: 80–109, 2016.

[4] Myers T G, Charpin J P F and Tshehla M S. The flow of a variable viscosity fluid between parallel plates with shear heating. Appl. Math. Model., 30: 799–815, 2006.

[5] Wang H, Dlugogorski B Z and Kennedy E M. Coal oxidation at low temperatures: oxygen consumption, oxidation products, reaction mechanism and kinetic modelling. Progress in Energy and Combustion Science, 29 (6): 487–513, 2003.

[6] Rosema A, Guan H and Veld H. Simulation of spontaneous combustion to study the causes of coal fires in the rujigou basin. Fuel, 80: 7–16, 2001.

[7] De Vries D A. The thermal conductivity of soil. PhD thesis, Agricultural University of Wageningen, 1952.