MISG 2018

Spontaneous Combustion of Stockpiled Coal

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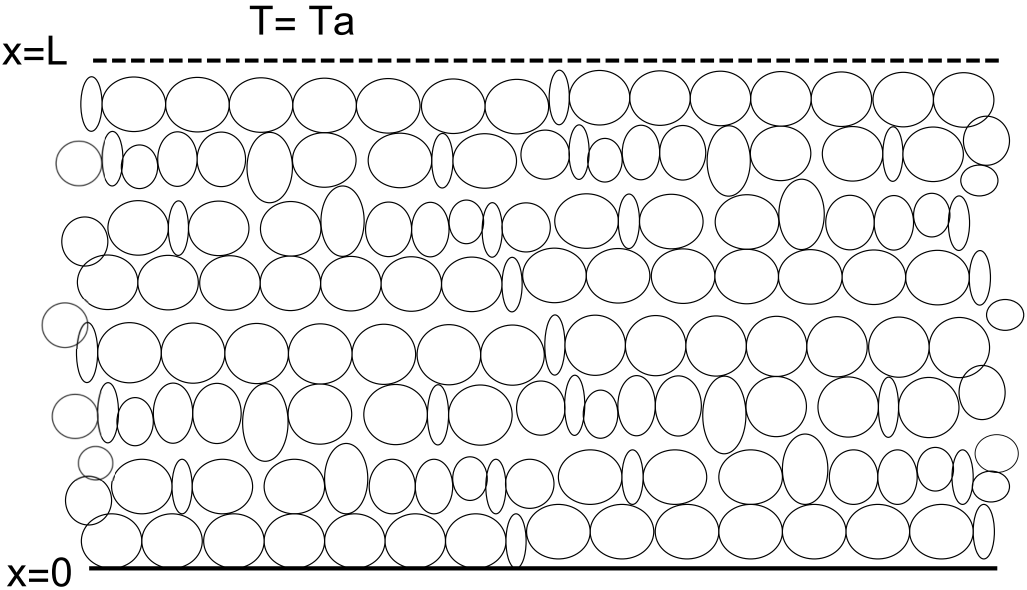
Introduction

- Coal Stockpiles - Transport, Storage, etc.
- Spontaneously catches fire.
- Chemical reactions release heat.
- $< 70° C$ - Low Temp: Adsorption.
- $> 70° C$ - High Temp: Oxidation.

Under what conditions does coal spontaneously combust?

How does shape affect combustion?

1D Bed Problem



1D Bed Problem

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

Subject to the initial and boundary conditions:

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

1D Bed Problem

The variables for non-dimensionalisation are:

$$\bar{T} = \frac{T - T_a}{\Delta T} \quad ; \quad \bar{t} = \frac{t}{\tau} \quad ; \quad \bar{x} = \frac{x}{L}$$

Where

$$\Delta T = \frac{qL^2}{\kappa} \quad ; \quad \tau = \frac{L^2}{\kappa} \quad ; \quad \kappa = \frac{k}{\rho c}$$

1D Bed Problem

The resulting equation, after dropping the bars and scaling, becomes

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

Subject to the non-dimensional initial and boundary conditions:

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

1D Bed Problem

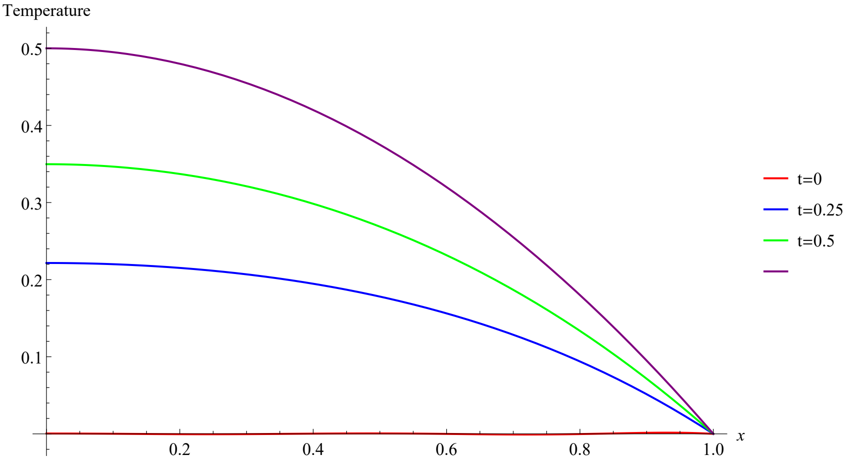


Figure: Temperature profile of analytical solution

$$T = \frac{1}{2}(1 - x^2)$$

Arrhenius Model

$$\rho c \frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial x^2} + X_a F H e^{\frac{-E}{RT}}$$

The dimensionless equation is given by:

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

Arrhenius Model

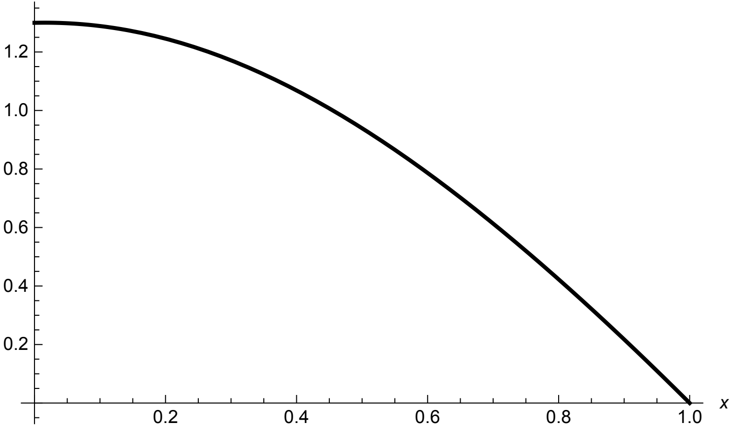


Figure: Temperature profile of analytical solution

$$L_{crit} \approx 38cm \qquad T_{max} \approx 60^{\circ}C$$

Coupled Model

$$(\rho c)_p T_t = k_p T_{xx} + XFHe^{-\frac{E}{RT}},$$

$$X_t + UX_x = DX_{xx} - XFe^{-\frac{E}{RT}}$$

Subject to the following initial and boundary conditions:

$$X(x,0) = X_a \quad ; \quad T(x,0) = T_a \quad ; \quad \left.\frac{\partial X}{\partial x}\right|_{x=0} = 0 \quad ; \quad \left.\frac{\partial T}{\partial x}\right|_{x=0} = 0$$

$$\left.\frac{\partial X}{\partial x}\right|_{x=L} = -h_x(X - X_a), \quad ; \quad k\left.\frac{\partial T}{\partial x}\right|_{x=L} = -h(T - T_a)$$

Coupled Model Results

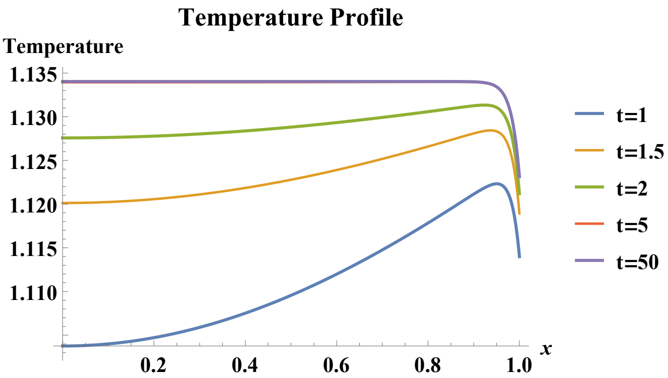


Figure: Temperature profile of numerical solution

Coupled Model Results

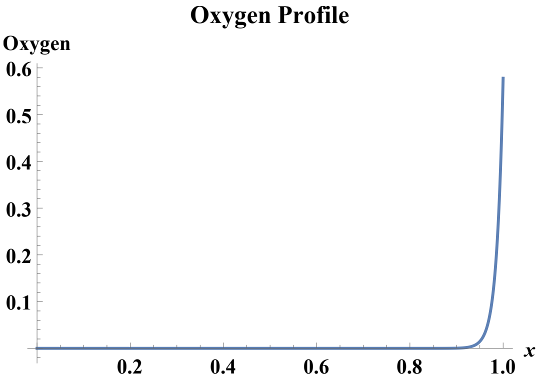


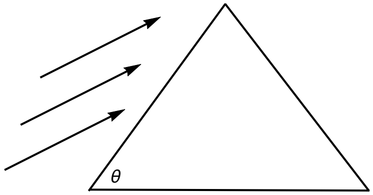
Figure: Oxygen profile of numerical solution

Air Flow and Oxygen Replacement

- Oxygen replacement is key for self heating
- Oxygen replacement is driven primarily by air flow
- 2 well known situations where spontaneous combustion does not occur: Well-sheltered or High Wind Flow
  - Well-sheltered prevents oxygen replacement, which reduces the possibility of self heating
  - High wind flows replaces oxygen, but also removes heat

Form of Air Flow

The important air flow is the horizontal component entering the stockpile. When the air penetrates sufficiently far it heats and moves upwards due to bouyancy. We are not sure what this component is, due to the various shapes of the pile and the fact that the air flow will be turbulent. But … we can make a relatively crude model because it is only the flow near the boundary that matters, since the oxygen quickly depletes inside the pile.



Effect of Porosity - Governing Equations

$$(\rho c)_p T_t = k_p T_{xx} + XFHe^{-\frac{E}{RT}},$$

$$X_t + UX_x = DX_{xx} - XFe^{-\frac{E}{RT}},$$

$$(\rho c)_p = (1-\phi)(\rho c)_c + \phi(\rho c)_a \approx (1-\phi)(\rho c)_c,$$

$$\rho_p = (1-\phi)\rho_c + \phi\rho_a \approx (1-\phi)\rho_c,$$

$$k_p = (1-\phi)k_c + \phi k_a \approx (1-\phi)k_c.$$

Effect of Porosity

This is not accurate, as k_p has been found experimentally to be

$$k_p = \frac{f(1-\phi)k_c + \phi k_a}{\phi + f(1-\phi)},$$

and

$$f = \frac{0.66}{1 + 0.125\frac{k_c}{k_a}} + \frac{0.33}{1 + 0.75\frac{k_c}{k_a}}.$$

This shows k_p decreases more rapidly.

$D = \phi D_a$ where D_a is the diffusivity of oxygen in air $\approx 2x10^{-5} m^2/s$

Conclusion

- Large piles are more likely to spontaneously combust
- Runaway temperatures also lead to combustion
- O_2 dynamics play a major role in stockpile heating
- Pile shapes and wind need to be done numerically
- Future work : look at oxycoal and moving boundary