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Theoretical analysis of coal stockpile self-heating

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ABSTRACT

This paper theoretically analyses the problem of coal stockpile self-heating under free convection (no wind) conditions. Scale analysis has been used to drive expressions for the stockpile temperature and inflection point (when the stockpile is completely dry) as functions of the key parameters including the coal type, moisture content, and particle diameter as well as the ambient air temperature. Theoretical predictions are then successfully compared with experimental data and CFD simulations results available in the open literature.

1. Introduction

By self-heating we mean the process of temperature rise in a medium due to internal heat generation from chemical or physical processes taking place within the reactive matter. For a wet coal stockpile, the main processes that take place simultaneously are the transfer of (internally-generated) heat and moisture (evaporation) to the ambient. Spontaneous combustion may happen when all of the generated heat within the reactive pile cannot be transferred away to the environment by natural convection. As such, a part of the generated heat is stored in the pile and overheats the coal to its thermal runaway point.

The time needed for the temperature to reach a critical value for moist coal is much longer than that required for a dry one [1–3]. Furthermore, the water transfer into coal can also be affected by the relative pressure [4,5]. Including the influence of chemical exothermic reactions on phase change of the moisture during the drying process, Dong [6] used a 1D mathematical model to determine the effect of moisture content on the maximum temperature rise in a coal stockpile. The influence of coal stockpile height, slope angle and moisture was investigated by Akgun and Essenhigh [7]. Their model predicts that the ignition temperature is a function of the bed porosity, pile shape, and the coal type and the time to ignition is usually in excess of half a month or more. Bouddour et al. [8] simplified mathematical models of heat and mass transfer in wet porous media using asymptotic expansions for periodic structures. A 2D CFD simulation is reported to investigate the wind effect on dry coal self-heating in [9].

There have been few studies that investigate the effects of moisture transport in reactive porous media on the heat generation process and water phase change. The present work offers scale analysis of self-heating within coal stockpiles of typical size and physical properties. Solutions allow the prediction of the coal temperature within the stockpile. The inflection point, the point in time when the coal stockpile water content first goes to zero is also of interest. The solution also gives the temperature at this point and the time at which it occurs. The former is a measure of coal self-heating while the latter gives an indication as to how much time the stockpile has before it poses a safety concern on its environment.

2. Mathematical modeling

In this work we consider stockpiles which have a geometry that can be represented by two spatial coordinates. The specific geometry we use for the analysis is depicted in Fig. 1 and translational symmetry is assumed in z-direction. This is representative of the typical shape of a coal stockpile. Using the Boussinesq approximation to model the fluid density variation, the volume-averaged governing equations [10–17] to cover porous domain, can be written as

Continuity:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (1)$$

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Nomenclature

A	constant (s^{-1})
C	concentration (mol kg^{-1})
C_F	form drag coefficient (C_F=0.55)
C_P	specific heat at constant pressure (J kg^{-1} K^{-1})
d	solid particle diameter (m)
D	diffusion coefficient (m^2 s^{-1})
D_1	characteristic length (m)
D_m	isothermal mass transfer coefficient (m^2 s^{-1})
D_w	isothermal total mass transfer coefficient (m^2 s^{-1})
D_T	non-isothermal mass transfer coefficient (m^2 s^{-1} K^{-1})
E	activation energy (J mol^{-1})
g	gravitational acceleration (m s^{-2})
h	enthalpy (J kg^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
K	permeability of the porous medium (m^2)
L	length of the stockpile (m)
$\dot{m}$	rate of moisture evaporation (kg s^{-1})
M	mass of porous media (kg)
M^*	$\frac{\dot{m}}{M}$ (s−1)
O	symbol to show order of magnitude
p	pressure (Pa)
Q	volumetric heat generation rate (W m^{-3})
Q_1	heat of reaction (J kg^{-1})
R	universal gas constant (J mol^{-1} K^{-1})
t	time (s)
T	temperature (K)
(u,v,w)	velocity components (m s)
v^*	velocity scale (m s^{-1})
V	volume of the stockpile (m^3)
(x,y,z)	Cartesian coordinates (m)

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
β	thermal expansion coefficient (K^{-1})
ε	porosity
θ	porous medium (stockpile) side angle
μ	viscosity (Pa s)
ν	fluid kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})
ω	moisture content (kg kg^{-1} of dry porous)

Subscripts

a	air
dry	dry stockpile
e	effective
f	fluid phase
i	initial
l	liquid
s	solid
sat	saturation
t	total
v	vapor
vl	difference between vapor and liquid

Momentum:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\varepsilon\frac{\partial p}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-\varepsilon\left(\frac{\upsilon u}{K}+C_F\varepsilon u\sqrt{\frac{u^2+v^2}{K}}\right) \tag{2a}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\varepsilon\frac{\partial p}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)-\varepsilon\left(\frac{\upsilon v}{K}+C_F\varepsilon v\sqrt{\frac{u^2+v^2}{K}}\right)-\varepsilon g\beta(T-T_i) \tag{2b}$$

Energy:

$$(\rho C_p)_e\frac{\partial T}{\partial t}+(\rho C_p)_a\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k_e\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+(1-\varepsilon)Q+M^*\rho_e h_{vl} \tag{3}$$

The source terms are oxidation (heat generation) and evaporation, respectively. Here, the evaporation rate divided by the porous medium mass is denoted as $M*$ which changes with time. In order to simplify the mathematical formulation, we assume that the heat release is governed by a simple one-step reaction. This is a rough approximation, because it is well known that the oxidation of coal is governed by numerous processes like formation of volatile compounds, pore diffusion and heterogeneous reaction, and can be locally diffusion or reaction limited [23]. These processes could be accounted for by hierarchical modeling concepts, but this is out of the scope of this work and subject of future research. Therefore the oxidation term is be modeled as:

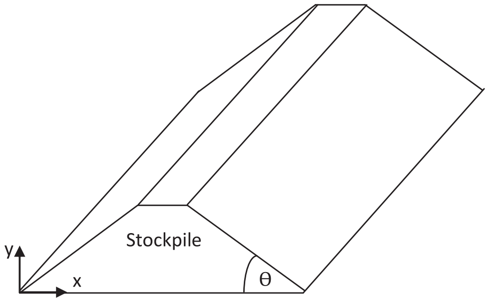

Fig. 1. Schematic representation of the problem.

$$Q=\rho_a Q_1 A\exp\left(\frac{-E}{RT}\right) \tag{4}$$

where Q_1 is the heat of reaction, A is the pre-exponential factor, R is the universal gas constant and E is the activation energy [10]. Note that the fluid (and thus effective porous) properties in the above equations change with time. As time evolves and water evaporates, the properties change. Although the values of the heat of reaction, the pre-exponential factor, and the activation energy for this global reaction (in contrast to reaction parameters based on elementary reactions [19]) depend on local conditions like moisture content, temperature etc. and may change with time [20–24], we assume, for simplicity, constant values. An extension to moisture-dependent values is possible in the model; subject of future work. Assuming local thermal equilibrium between the solid and fluid phases in the porous medium, a single energy equation model, like Eq. (3), is adopted to study the heat transfer from the stockpile. Numerical simulation of the stockpile based on local thermal non-equilibrium (two-equation model) showed results very close to those obtained from Eq. (3) as reported by Ejlali [18]. Thus, Eq. (3) is preferred to a more complex two-equation model in this work.

The conservation equations for moisture in liquid and vapor forms and the energy equation are derived based on Whitaker's theory as detailed by Kallel et al. [12]. The generic forms of the unsteady equations for moisture movement in the solid porous