Combustion Reactivity of Rice Husk: 
An Experimental and Numerical Investigation

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The combustion reactivity of rice husk from New South Wales, Australia was measured by heating cubic baskets in controlled environment and monitoring the centre temperature. Frank-Kamenetskii’s ignition theory was used to calculate the activation energy. Results agreed well with tests on other cellulosic materials. Numerical simulations of temperature changes were carried out, using a special technique to deal with non-linearities in the heat conduction equation. The numerical results indicate that the time factor should be taken into account when evaluating self-combustion risks.

Keywords: combustion, reactivity, kinetics, rice husk, heat conduction, numerical method.

Rice husk, like other cellulosic materials, is used as a cheap and convenient source of energy in rural areas. It is usually stored in large volumes, such as open stockpiles or in silos. A major hazard of this practice is that the material has a propensity for self-heating. Depending on the ambient temperature and amount of material present, the internal temperature of a mass may rise to a point where spontaneous combustion occurs. To avoid such an occurrence, it is necessary to predict safe storage conditions for the material.

Safety criteria are usually obtained using Frank-Kamenetskii’s steady state analysis, which yields a simple relationship between ambient temperature and critical storage size. Laboratory tests are then carried out to determine critical temperatures for a range of sample size, and the results extrapolated to realistic storage conditions. The analysis does not provide a means of calculating times to ignition.

The Fourier heat conduction equation with internal heat generation and constant thermal conductivity can be written:

\[ \sigma c \frac{\partial T}{\partial t} = k \nabla^2 T + \sigma q A \exp(-E/RT) \] (2)

When expressed in terms of a dimensionless temperature \( \theta \):

\[ \theta = \frac{E}{RT_a^2} (T - T_a) \] (3)

equation (2) becomes

\[ \frac{\partial \theta}{\partial \tau} = \nabla^2 \theta + \delta \cdot \exp(-\frac{\theta}{1 + \epsilon \theta}) \] (4)

where

\[ \delta = \frac{E \sigma q A \cdot \exp(-R/RT_a)}{kRT_a^2} \] (5)

\( \epsilon = RT_a/E \ll 1 \) usually, therefore equation 4 can be rewritten

\[ \frac{\partial \theta}{\partial \tau} = \nabla^2 \theta + \delta \cdot \exp(\theta) \] (6)

where \( \tau = \text{dimensionless time, } \alpha t/r_0^2 \).

The condition for steady state is then

\[ \nabla^2 \theta + \delta \cdot \exp(\theta) = 0 \] (7)

and boundary conditions are that \( T + T_0 \) (with infinite heat transfer coefficient) which translates to \( \theta = 0 \) at the outside surface of the material at all \( t \). Steady solutions to the heat balance equation, i.e. to Eq.7, exist only for values of \( \delta \) below a critical value \( \delta_{crit} \), which in turn depends on the shape of the reacting mass. \& it values for common geometries have been

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Nomenclature

- \( A \) rate constant, \( \text{s}^{-1} \)
- \( c \) specific heat, \( \text{J kg}^{-1} \text{K}^{-1} \)
- \( E \) activation energy, \( \text{J mol}^{-1} \)
- \( k \) thermal conductivity, \( \text{W m}^{-1} \text{K}^{-1} \)
- \( G \) virtual heat, \( \text{J kg}^{-1} \)
- \( H \) enthalpy, \( \text{J kg}^{-1} \)
- \( q \) heat of reaction per unit mass of material, \( \text{J kg}^{-1} \)
- \( Q \) heat generation rate, \( \text{W kg}^{-1} \)
- \( \tau_0 \) Frank-Kamenetskii radius, \( \text{m} \)
- \( R \) gas constant, \( \text{J mol}^{-1} \text{K}^{-1} \)

For a cube, \( \delta_{\text{crit}} \approx 3.663 \) provided that the Frank-Kamenetskii radius \( \tau_0 \) is taken as 1.194 times the cube’s half side, or \( \delta_{\text{crit}} \approx 2.60 \) if \( \tau_0 \) is taken as the cube’s half side.

For a given material and geometry, \( T_{a, \text{crit}} \), the critical boundary temperature, depends on \( \tau_0 \). By measuring \( T_{a, \text{crit}} \) for samples of different sizes \( \tau_0 \) and density \( \sigma \), and plotting \( \ln(\delta_{\text{crit}} T_{a, \text{crit}}/\sigma \tau_0^2) \) against \( 1/T_{a, \text{crit}} \), Eq. 7 predicts that a straight line should be obtained according to

\[
\ln\left(\frac{\delta_{\text{crit}} T_{a, \text{crit}}^2}{\sigma \tau_0^2}\right) = \ln \frac{E q A}{R k} - \frac{E}{RT_{a, \text{crit}}} \quad (8)
\]

A plot of \( \ln(\delta_{\text{crit}} T_{a, \text{crit}}/\sigma \tau_0^2) \) against \( 1/T_{a, \text{crit}} \) will therefore enable the values of the activation energy \( E \) and, with supplementary information, the pre-exponential factor \( A \) to be calculated.

Numerical Solution

A numerical solution of the heat conduction equations enables the validity of the Frank-Kamenetskii model to be checked, which would be useful since from a mathematical point of view, this model is not entirely rigorous but relies on an approximate \( \delta_{\text{crit}} \) value for shapes other than the infinite slab and infinite cylinder.

Either the steady-state equation or the unsteady-state equation can be solved. Since the problem is highly non-linear (strong dependence of heat generation rate on temperature), solution of the steady-state problem would involve lengthy iterations which would make it no more attractive, and less informative, than an unsteady-state solution. Therefore the latter course was chosen.

The exponential dependence of the heat generation rate on temperature makes the problem very difficult to solve numerically, especially near the ignition point. The method used was a finite difference method with modifications by Pham\(^6,7\) which enables non-linear heat conduction problems to be solved by an implicit stepping method without iteration. Pham defined a function, termed the "virtual heat", which for the Crank-Nicolson method takes the form

\[
G(T) = H(T) - (1/2)\delta t Q(T) \quad (9)
\]

The finite-difference calculation is carried out in the usual manner, using a well-known stepping method such as Crank-Nicolson. The virtual heat at each node \( i \) is then calculated from

\[
G_i^{n+1} = G(T_i^n) + \sigma c \left( T_i^{n+1} - T_i^n \right) \quad (11)
\]

and the new temperature corrected to

\[
T_i^{n+1 \text{(corrected)}} = T(G_i^{n+1}) \quad (12)
\]

where the superscript \( n \) refers to values at time \( t \) and \( n + 1 \) to values at time \( t + \delta t \). No iteration is needed in this method.

MATERIALS AND METHODS

All tests were carried out in an electrically powered, recirculating air oven. Air temperature is controlled by a thermostat with 1 K graduations, with a maximum setting of 250°C.

Rice husk samples were contained in cubic baskets made of stainless steel mesh. All baskets have removable lids, and provision for insertion of a thermocouple. The temperature at the centre of the sample cube and the oven temperature were measured...