A Mathematical Model Of Solar Drying Of Rice

Pyseth Meas, Massey University  
Anthony H.J. Paterson, Massey University  
Donald J. Cleland, Massey University  
John E. Bronlund, Massey University  
A. John Mawson, London South Bank University  
Allan Hardacre, Massey University  
Joseph F. Rickman, International Rice Research Institute

Recommended Citation:  
DOI: 10.1515/1556-3758.2380  
©2012 De Gruyter. All rights reserved.
A Mathematical Model Of Solar Drying Of Rice

Pyseth Meas, Anthony H.J. Paterson, Donald J. Cleland, John E. Bronlund, A. John Mawson, Allan Hardacre, and Joseph F. Rickman

Abstract

A mathematical model describing the heat and moisture transfer within a solar drying system of rice was formulated. A numerical solution using MATLAB was implemented due to the many coupled PDEs and nonlinear algebraic equations. The model was checked for a range of the space steps and by comparison to analytical solutions for completed situations and was shown to contain no significant numerical errors. After estimating the best values and uncertainties of the system inputs the model was validated by comparison with experimental data for solar drying of rice. It was shown to be a very good mechanistic tool with advantages of simplicity and practical accuracy. The model accurately predicted the drying time and the temperature, and moisture content (MC) within the bed during drying except when a polystyrene drying pad was used. However, the model did not predict the experimental bed water activity (relative humidity) consistently well.

KEYWORDS: rice, drying, solar, mathematical model

Author Notes: Funding provided by the New Zealand Ministry of Foreign Affairs in the way of an NZAID Scholarship, by The International Rice Research Institute, the Agricultural Quality Improvement Program (AQIP) of the Cambodian Ministry for Industry, Mines and Energy and The British and American Tobacco Company in Cambodia. No restrictions have been placed on any of the work to be published by any of these agencies and their help is gratefully acknowledged.
1. INTRODUCTION

The solar drying of rice is a complicated and poorly controlled process involving the transfer of heat and moisture which are influenced by climatic and operator factors. Solar radiation is converted to thermal energy in the rice bed. There is the diffusion of moisture from the centre of each kernel to the surface of the kernel, evaporation from the surface of the kernel to the air space around it, the movement by diffusion or mass transfer from the inside of the bed to the surface of the bed and subsequently into the ambient air. The drying capacity of the air can be very large and can cause serious damage to the grain (Bhashyam et al., 1975; Aguerre et al., 1986; Ekstrom et al., 1966 and Imoudu and Olufayo, 2000).

To maximise the throughput of drying while maintaining the grain quality, mathematical modelling of the drying process has been found to offer an effective tool to better understand the process (Sharma et al., 1982; Yang et al., 2001; Thieelen et al., 2001). Drying models have been developed that are useful tools for predicting the moisture content (MC) and temperature distributions inside the kernels, within the drying bed which can be used to optimise the drying and tempering processes to improve the grain quality. They are helpful in designing new or improving existing drying systems or for the control of the drying operation (Sharma et al., 1982; Yang et al., 2001).

This study was undertaken to develop and validate a mathematical model for the heat and moisture transport within the drying bed of rice during solar drying. The model is intended to be used as a simulation tool capable of predicting the patterns of the grain temperature, MC and air relative humidity (RH) at different layers of the drying bed as a function of time during solar drying, to provide additional detail on the local conditions within the bed, to better understand the drying process and the interactions between variables and to predict the drying time and alternative parameters that might be correlated with the key quality variable, head rice yield (HRY).

2. MATHEMATICAL MODEL

2.1 Conceptual model development

To make the model applicable to most of the solar drying configurations likely to be used by rice farmers in Cambodia, four different ways that the grain is exposed to the sun were considered in this study. Figure 1 illustrates that the sun is the heat source and gives the physical situation and modes of transport of heat and moisture included in the model.
When the bed was not shaded or covered (Fig 1.a), the solar radiation falling on the bed surface will be partly absorbed and partly reflected. The absorbed radiation heats the surface. A part of this heat is utilized to evaporate the moisture from the surface to the surrounding air, while the remaining part is conducted or convected into the interior of the bed or lost through convection to the air and through convection to the ground or other materials placed below the bed. When the rate of gain by radiation exceeds the losses by conduction and evaporation, the bed will heat up and cause accelerated drying and moisture diffusion. Moisture within the kernels evaporates into the air within the bed and then diffuses out to the bed surface into the air. In the materials below the rice bed (husk, mat, polystyrene and the soil) moisture was assumed to be in equilibrium between the material and the local air. In the bed, drying was considered to be limited by moisture transfer within the kernel and for drying to occur, the moisture content of air within the bed and that of the grain cannot be in equilibrium.
When the bed was covered by a water-proof tarpaulin (Fig 1b), the bed was assumed to not lose moisture to the air. The surface does receive the radiation directly from the sun. Instead the tarpaulin is heated by the solar radiation and then loses heat by convection to the air above and below the tarpaulin, conduction into the bed and reflection to the sky.

Similar mechanisms of heat and moisture transfer apply to the grain under both shading and direct covering (Fig 1c) or shading only (Fig 1d). The shading tarpaulin absorbs solar radiation and transfers it to the air by convection and to the bed surface or covering tarpaulin by radiation. The only difference is that the heat from the covering tarpaulin or rice bed surface is not radiated to the sky but to the underside of the shading tarpaulin. The conduction of heat and moisture within the bed for all drying methods are similar.

If the grain is dried on a tarpaulin or mat spread directly on soil, moisture transfer between the bed and the soil was assumed negligible. This was not the case for drying on a net where air was able to move freely under the grain bed.

The development of the model was based on the following physical processes:

- Temperature and moisture gradients develop through the bed depth.
- The solid (rice kernels) and gaseous phases in the bed were each considered as continuous with interaction over adjacent interfaces.
- Moisture diffusivity and thermal conductivity were treated as effective properties of the entire rice bed including grain and air.
- The rate of moisture leaving the bed depends on the vapour pressure difference between the kernel and the surrounding air environment.

The model equations were developed with the following assumptions:

- One-dimensional transfer of heat and moisture vertically through the rice bed.
- The surface of the grain kernels tend to rapidly equilibrate their MC with the humidity of the surrounding air.
- No gravitational effects on the system.
- At any position in the bed, the air and rice are in thermal equilibrium.
- The bulk and true densities, as well as the thermal properties of all the materials are constant and do not change with either temperature or MC.
- The temperature below the interface of material 3(soil) with material 4 (soil) in Figure 1 was constant.
- Negligible heat and moisture transfer resistance for the nylon net on which grain was dried.
Negligible moisture diffusion occurs through polystyrene pads on which the grain was dried.

Moisture transfer by air flow within the bed can be approximated by pseudo-diffusion

Temperature and MC within the beds are uniform at the start of drying and at the end of stirring

The grain bed does not perfectly contact the tarpaulin and mat, and

The tarpaulins have negligible thermal capacity.

2.2 Model formulation

To account for the simultaneous changes in the material conditions with locations and time, the heat (temperature) and mass (MC and RH) balances were formulated in the form of partial differential equations (PDEs).

Within the solid materials, Fourier’s law for conductive heat transfer in one dimension with an extra term to account for heat transferred by diffusing water vapour was employed (Bronlund, 1997). All symbols are defined in the nomenclature.

\[
\rho_m c_{pm} \frac{\partial T}{\partial t} = \lambda_m \frac{\partial^2 T}{\partial x^2} - D_{vm, eff} \cdot \epsilon_m h_g \frac{\partial^2 C}{\partial x^2}
\]

for \(0 < x < L_p, (m=1)\)

\(L_p < x < L_p + L_2, (m=2)\)

\(L_p + L_2 < x < L_p + L_2 + L_3, (m=3)\) and

\(t > 0.\)

If the drying was performed on a drying pad of husk placed upon the soil then the properties of rice, husk and soil would be used by using \(m = 1, 2 \text{ and } 3\), respectively as a parameter in the model. The energy balance for heat transfer at the bed surface was:
(I - S_1)(I - S_2)β_p A_{top} I + S_1(I - S_2)β_p A_{top} I_{sh} \\
+ S_1(I - S_2)F_{A1} \varepsilon_{tarp} \varepsilon_p A_{top} \sigma \left[ (T_{sh} + 273.15)^{\varepsilon_p} - (T_{x=0} + 273.15)^{\varepsilon_p} \right] \\
+ S_2 F_{A2} \frac{1}{\varepsilon_{tarp} \varepsilon_p + 1} A_{top} \sigma \left[ (T_{cov} + 273.15)^{\varepsilon_p} - (T_{x=0} + 273.15)^{\varepsilon_p} \right] \\
+ S_2 A U_{tarp/p} (T_{cov} - T_{x=0}) - D_{vp.eff} \varepsilon_p h_{gin} A \frac{\partial C}{\partial x} \\
= (I - S_1)(I - S_2) \varepsilon_p A_{top} \sigma \left[ (T_{x=0} + 273.15)^{\varepsilon_p} - (T_{sky} + 273.15)^{\varepsilon_p} \right] \\
+ S_1(I - S_2) \varepsilon_p A_{top} \sigma \left[ (T_{x=0} + 273.15)^{\varepsilon_p} - (T_a + 273.15)^{\varepsilon_p} \right] \\
- (I - S_2)k_e h_{gout} A(C_i - C_a) + (I - S_2)h_{gin} A_{top} (T_{x=0} - T_a) - \lambda_p A \frac{\partial T}{\partial x} \\
\text{for } x = 0 \text{ and } t > 0.

The switches S_1 and S_2 correspond to the presence (S = 1) or not (S = 0) of the shade and direct cover, respectively.

Assuming that half the thickness of the paddy kernel (d) on the bed surface was exposed to the ambient air or the sun then:

\[ A_{top} = a_k V_{top} = a_k A \frac{d_k}{2} \] (3)

To describe the heat transfer between the bed and material 2 or between materials 2 and 3, the following energy balance was developed and included a heat transfer resistance, especially when another material such as a tarpaulin was used at the interface:

\[ \lambda_m \frac{\partial T}{\partial x} \bigg|_m = \lambda_{tarp} \frac{\partial T}{\partial x} \bigg|_m = \lambda_{m+1} \frac{\partial T}{\partial x} \bigg|_{m+1} \] (4)

for \( x = L_p \) (m=1) or \( x = L_p + L_2 \) (m=2) and \( t > 0 \).

For the boundary between material 3 and the ground, the temperature was assumed to be equal to the constant deep ground temperature:

\[ T_x = T_{gr} \] (5)

for \( x = L_p + L_2 + L_3 \) and \( t > 0 \).
For the shading tarpaulin, an energy balance describing the steady-state heat transfer was written as:

\[
A\beta_{\text{tarp}}.I = \varepsilon_{\text{tarp}}.A\sigma\left[\left(T_{\text{sh}} + 273.15\right)^{4} - \left(T_{\text{sky}} + 273.15\right)^{4}\right] + S_{\text{A}}.F_{\text{A}}.\varepsilon_{\text{tarp}}.A\sigma\left[\left(T_{\text{sh}} + 273.15\right)^{4} - \left(T_{\text{cov}} + 273.15\right)^{4}\right] \\
+ \left(1 - S_{\text{A}}\right).F_{\text{A}}.\varepsilon_{\text{tarp}}.\varepsilon_{\text{p}}.A\sigma\left[\left(T_{\text{sh}} + 273.15\right)^{4} - \left(T_{\text{cov}} + 273.15\right)^{4}\right] + 2Ah\left(T_{\text{sh}} - T_{a}\right)
\]

(6)

Rearranging Equation (6) yielded:

\[
T_{a} = \frac{2hT_{a} + \beta_{\text{tarp}}.I}{2h}
\]

(7)

This was applied when shading was applied \((S_{\text{I}} = 1)\) e.g. when the time of day was between \(11:00 \leq t \leq 14:00\).

For the covering tarpaulin, an energy balance describing the steady-state heat transfer was written as:

\[
\left(1 - S_{\text{I}}\right).A\beta_{\text{tarp}}.I + S_{\text{I}}.A\beta_{\text{tarp}}.I_{\text{sh}} + S_{\text{I}}.F_{\text{A}}.\varepsilon_{\text{tarp}}.A\sigma\left[\left(T_{\text{sh}} + 273.15\right)^{4} - \left(T_{\text{cov}} + 273.15\right)^{4}\right] \\
= \left(1 - S_{\text{I}}\right).\varepsilon_{\text{tarp}}.A\sigma\left[\left(T_{\text{cov}} + 273.15\right)^{4} - \left(T_{\text{sky}} + 273.15\right)^{4}\right] \\
+ F_{\text{A}}.\left(\frac{1}{\varepsilon_{\text{tarp}}} + \frac{1}{\varepsilon_{\text{p}}}\right) - \frac{1}{\varepsilon_{\text{tarp}}}A\sigma\left[\left(T_{\text{cov}} + 273.15\right)^{4} - \left(T_{\text{c}} + 273.15\right)^{4}\right] \\
+ Ah\left(T_{\text{cov}} - T_{a}\right) + A.U_{\text{tarp/p}}.\left(T_{\text{cov}} - T_{x=0}\right)
\]

(8)

The thermal resistance for conduction from the covering tarpaulin to the bed surface is

\[
R_{\text{tarp/p}} = \frac{1}{U_{\text{tarp/p}}} = \frac{L_{\text{tarp}}}{\lambda_{\text{tarp}}} + L_{a} = \frac{\lambda_{a}L_{\text{tarp}} + \lambda_{\text{tarp}}L_{a}}{\lambda_{\text{tarp}}\lambda_{a}}
\]
The temperature of the covering tarpaulin could be expressed as

\[
T_{\text{cov}} = \frac{h T_e + U_{\text{app}} (T_{\text{v,0}} + \beta_{\text{app}} (1 - S_I) I + S_I I_{\text{sh}}) + \varepsilon_{\text{app}} \sigma \left[ (T_{\text{sh}} + 273.15) - (T_{\text{v,0}} + 273.15) \right]}{h + U_{\text{app}}}
\]

\[
F_{\text{tot}} \left( \frac{I}{\varepsilon_{\text{app}} - \varepsilon_p} \right) - \frac{I}{\varepsilon_{\text{app}} - \varepsilon_p} - I
\]

\[
\frac{T_{\text{cov}}}{T_e} + U_{\text{app}} (T_{\text{v,0}} + \beta_{\text{app}} (1 - S_I) I + S_I I_{\text{sh}})
\]

\[
\frac{h + U_{\text{app}}}{h + U_{\text{app}}}
\]

\[
\frac{h + U_{\text{app}}}{h + U_{\text{app}}}
\]

for \( x = 0, S_2 = 1 \) and when the time of day was between \( 11:00 \leq t \leq 14:00 \).

The rate of moisture transfer in the grain kernels (drying rate) at any point in the bed was approximated as a first order approach to the equilibrium MC

\[
\frac{\partial MC}{\partial t} = -k (MC - MC_e) + B
\]

\[
(10)
\]

The moisture transfer in the air within the grain bed was defined using Fick’s law for diffusion in one dimension including a term for the rate of moisture transfer between the air space and the drying grain kernels.

\[
\frac{\partial C}{\partial t} = D_{\text{v, eff}} \frac{\partial^2 C}{\partial x^2} + \rho_{\text{v, eff}} \left( -\frac{\partial MC}{\partial t} \right)
\]

\[
(11)
\]

for \( 0 < x < L_p, (m = 1) \) and \( t > 0 \).

The rate of moisture transfer in the air within materials 2 and 3 (Figure 1) is defined as

\[
\frac{\partial C}{\partial t} = D_{\text{v, eff}} \frac{\partial^2 C}{\partial x^2}
\]

\[
(12)
\]

where \( D_{\text{v, eff}} = \frac{D_{\text{v, eff}}}{I + k''} \) and \( k'' = \frac{\rho_{\text{v, eff}} n_{\text{s, v, eff}} P_{\text{tot}} \cdot P_a}{\varepsilon_m \cdot P_{\text{v, eff}} (18 \rho_a + 29 C)^2} \)

for \( L_p < x < L_p + L_2, (m = 2) \) and for \( L_p + L_2 < x < L_p + L_2 + L_3, (m = 3) \).
A heat balance describing the moisture movement at this boundary of this bed was written as

\[ D_{\text{vp, eff}} \cdot \varepsilon_p \cdot A \frac{\partial C}{\partial x} = (1 - S_z) k_y \cdot A (C_{x=0} - C_a) \] (13)

for \( x = 0 \) and \( t > 0 \).

For the bottom of the grain bed or bottom of material 2, a moisture balance describing the moisture diffusion was written as

\[ D_{\text{vm, eff}} \frac{\partial C}{\partial x} \bigg|_{m} = \frac{1}{R_{\text{MTm/m+1}}} (C_m - C_{m+1}) = D_{\text{vm, eff}} \frac{\partial C}{\partial x} \bigg|_{m+1} \] (14)

for \( x = L_p, (m = 1) \) or \( x = L_p + L_2, (m = 2) \) and \( t > 0 \).

Because no mass transfer is assumed to occur at the bottom of material 3:

\[ D_{\text{vm, eff}} \frac{\partial C}{\partial x} = 0 \] (15)

for \( x = L_p + L_2 + L_3, m = 3 \) and \( t > 0 \).

At the start of the drying:

\[ T = T_a \] (16)

for the bed \((0 \leq x \leq L_p)\) and for husk, mat, polystyrene, tarpaulin and net \((L_p \leq x \leq L_p + L_2)\) if these materials are used.

\[ T_i = T_{gr} \] (17)

for \( x > L_p \) if no husk, mat or polystyrene was used as material 2, or for \( x > L_p + L_2 \) if husk, mat or polystyrene was used as material 2.

\[ MC = MC_i \] (18)

for the grain bed or \( 0 \leq x \leq L_p \).
The moisture content in the air was calculated using:

\[
C = C_i = \frac{0.018RH_iP_{w}(T_i)}{R(T_i + 273.15)}
\]  

(19)

for \(0 \leq x \leq L_p + L_2 + L_3\).

When the treatment involved the bed being stirred, the simulation was stopped at the point in time when stirring occurred, the temperature and the MC of the grain at the moment were taken to be the averages of all the nodes within the bed, and the simulation was restarted with all the nodes reset to the average values. The average values are defined by:

\[
T = T_{\text{average}} = \frac{\int_0^{L_p} T \, dx}{L_p}
\]  

(20)

for \(0 \leq x \leq L_p\) at \(t = t_{\text{stir}}\).

\[
MC = MC_{\text{average}} = \frac{\int_0^{L_p} MC \, dx}{L_p}
\]  

(21)

for \(0 \leq x \leq L_p\) at \(t = t_{\text{stir}}\).

2.3 Finite difference solution

As there were many coupled PDEs describing transport of heat and mass in the model and some of the algebraic equations were nonlinear, it was difficult to solve the problem analytically and thus numerical solutions were developed. Because rapid changes in the variables were not observed and stability problems were unlikely, an explicit finite differences scheme, which is one of the most common and easiest methods available to solve the models numerically, was chosen using the nodal grid given in Figure 2.

There are \(J + \frac{1}{2}, K,\) and \(L\) space steps of \(\Delta x_p,\) or \(\Delta x_{m=1,}\) \(\Delta x_2\) and \(\Delta x_3\) assigned in the rice bed, material 2 and 3 of \(L_p, L_2 \) and \(L_3\) depths, respectively. To avoid having a node that contained two materials as well as the complexity caused by placing an interface between the two materials, the bottom node of each exposed material (i.e. \(J+1, J+K+1\) or \(J+K+L+1\)) was located half a space step above the bottom of the material. Node 1 (\(j = 1\)) was located at the very surface of
the grain bed with a space step of $\Delta x_p/2$. The top nodes of materials 2 and 3 were located half a space step below the corresponding material boundary.

2.4 ODE Equations

The following are the complete sets of the ordinary differential equations (ODEs) describing the heat and moisture transfer within the drying system resulting from the energy and moisture balances for each node. For the bed surface,
\[
\frac{\partial Q_i}{\partial t} = -(1 - S_i) h_i \dot{a}_k A \frac{d_i}{2} T_i + (1 - S_j) h_i \dot{a}_k A \frac{d_i}{2} T_i - \frac{\lambda_i}{\rho_i \Delta X_p} \frac{dT_i}{\Delta X_p} + \frac{\lambda_i}{\rho_i \Delta X_p} \frac{dT_i}{\Delta X_p} + (1 - S_i) \beta_i \dot{a}_k A \frac{d_i}{2} + (1 - S_i) \beta_i \dot{a}_k A \frac{d_i}{2} I_{sh} + S_i (1 - S_i) \beta_i \dot{a}_k A \frac{d_i}{2} - 1 - S_i \beta_i \dot{a}_k A \frac{d_i}{2} I_{sh} \]
\[
+ \frac{S_i}{F_{A_2}} \left[ \frac{1}{\epsilon_{tar} + \epsilon_{p}} - 1 \right] \dot{a}_k A \frac{d_i}{2} \sigma \left[ (T_{cov} + 273.15)^{\epsilon_i} (T_i + 273.15)^{\epsilon_i} \right] \]
\[
+ \frac{S_i}{F_{A_2}} \left[ \frac{1}{\epsilon_{tar} + \epsilon_{p}} - 1 \right] \dot{a}_k A \frac{d_i}{2} \sigma \left[ (T_{cov} + 273.15)^{\epsilon_i} + (T_i + 273.15)^{\epsilon_i} \right] \]
\[
+ \frac{S_i}{F_{A_2}} \left[ \frac{1}{\epsilon_{tar} + \epsilon_{p}} - 1 \right] \dot{a}_k A \frac{d_i}{2} \sigma \left[ (T_{cov} + 273.15)^{\epsilon_i} + (T_i + 273.15)^{\epsilon_i} \right] \]
\[
- (1 - S_i) (1 - S_j) \epsilon_i \dot{a}_k A \frac{d_i}{2} \sigma \left[ (T_{cov} + 273.15)^{\epsilon_i} - (T_i + 273.15)^{\epsilon_i} \right] \]
\[
- S_i (1 - S_i) \epsilon_i \dot{a}_k A \frac{d_i}{2} \sigma \left[ (T_i + 273.15)^{\epsilon_i} - (T_i + 273.15)^{\epsilon_i} \right] \]
\[
- (1 - S_i) \dot{k}_1 \frac{\partial}{\partial t} \left( h_{fg} + c_{pv} \frac{T_i + T_{cov}}{2} \right) (C_i - C_{a}) \]
\]

where \(Q_i\) is the amount of energy (J) in the node. The temperature was calculated from \(Q_i\) by:
\[
T_i = \frac{2Q_i - C_i \epsilon_i \dot{a}_k A \Delta X_p h_{fg}}{(1 - \epsilon_i) \rho_i A \Delta X_p c_{pp} + (1 - \epsilon_i) \rho_i A \Delta X_p c_p M_i + \epsilon_i \rho_i A \Delta X_p c_m + \epsilon_i \rho_i A \Delta X_p c_{pv} M_i + \epsilon_i \rho_i A \Delta X_p c_{pv} C_i}
\]

The moisture concentration was calculated from
\[
\frac{\partial C_i}{\partial t} = \frac{2D_{vp.eff}(C_i - C_{a})}{\Delta X_p^2} + \frac{\rho_i \left[k(MC_i - MC_{el}) - B\right]}{\epsilon_i \dot{a}_k A \Delta X_p} \frac{(1 - S_i) 2k_y (C_i - C_{a})}{\epsilon_i \dot{a}_k A \Delta X_p}
\]

\[
\frac{\partial MC_i}{\partial t} = -k(MC_i - MC_{el}) + B \frac{\left[k(MC_i - MC_{el}) - B\right]}{\Delta X_m}
\]

for \(j = 1\) and \(t > 0\).

For the grain bed, material 2 and material 3, the rate of change of the energy content of nodes within the grain bed (\(2 \leq j \leq J, m = 1\)) or the other
materials \((J+3 \leq j \leq J+K, \ m = 2\) and \(J+K+3 \leq j \leq J+K+L, \ m = 3\) were approximated by:

\[
\frac{\partial Q_j}{\partial t} = \frac{\lambda_m \cdot A \left( T_{j-1} - 2T_j + T_{j+1} \right)}{\Delta x_m} + \frac{D_{\text{vm,eff}} \cdot \varepsilon_m \cdot A \left( h_{fg} + c_{pv} \frac{T_{j+1} + T_j}{2} \right)(C_{j+1} - C_j)}{\Delta x_m} - \frac{D_{\text{vm,eff}} \cdot \varepsilon_m \cdot A \left( h_{fg} + c_{pv} \frac{T_j + T_{j-1}}{2} \right)(C_{j+1} - C_j)}{\Delta x_m}
\]

\[
T_j = \frac{Q_j - C_j \cdot \varepsilon_m \cdot A \cdot \Delta x_m \cdot h_{fg}}{(1 - \varepsilon_m) \rho_m \cdot A \cdot \Delta x_m \cdot c_{pm} + (1 - \varepsilon_m) \cdot \rho_m \cdot A \cdot \Delta x_m \cdot c_{pm} \cdot MC_j + \varepsilon_m \cdot \rho_m \cdot A \cdot \Delta x_m \cdot c_{pm} + \varepsilon_m \cdot A \cdot \Delta x_m \cdot c_{pm} \cdot C_j}
\]

The moisture balances for the air associated with the nodes within the rice bed \((2 \leq j \leq J, \ m = 1)\) was given by

\[
\frac{\partial C_j}{\partial t} = \frac{D_{\text{vp,eff}} \left( C_{j-1} - 2\ebj + \ebj + 1 \right)}{\Delta x_p^2} + \rho_{\text{vp}} \left[ k \left( MC_j - MC_{ej} \right) - B \right]
\]

The moisture balances for the air associated with the nodes within material 2 \((J+3 \leq j \leq J+K, \ m = 2)\) and material 3 \((J+K+3 \leq j \leq J+K+L, \ m = 3)\) were given by

\[
\frac{\partial C_j}{\partial t} = \frac{D_{\text{vm,eff}} \left( C_{j-1} - 2\ebj + \ebj + 1 \right)}{\Delta x_m^2}
\]

The rate of moisture drying out from a grain kernel for a node within the bed \((2 \leq j \leq J)\) was given by:

\[
\frac{\partial MC_j}{\partial t} = -k \left( MC_j - MC_{ej} \right) + B
\]

The rate of change of the energy content of the nodes at \(j = J+1, \ (m = 1)\) and \(j = J +K+1, \ (m = 2)\) was given by:
\[
\frac{\partial Q_j}{\partial t} = \frac{\lambda_m A(T_{j-1} - T_j)}{\Delta x_m} + \frac{1}{\lambda_{m+1} A} \left( \frac{2 \varepsilon_m \varepsilon_{m+1} D_{\text{vm eff}} \cdot D_{\text{vm+1 eff}} A(C_{j+1} - C_j)}{\Delta x_m \varepsilon_{m+1} D_{\text{vm+1 eff}}} + \frac{2 \lambda_m \lambda_{m+1} R_{\text{m+1/m}}}{\Delta x_m} \right) h_{fg} + c_{pv} \frac{T_{j+1} + T_j}{2} \]

\[
= \frac{2 \lambda_m \lambda_{m+1} A(T_j - T_{j-1})}{\Delta x_m + \frac{2 \lambda_m \lambda_{m+1} R_{\text{m+1/m}}}{\Delta x_m}} + \frac{D_{\text{vm eff}} \cdot \varepsilon_m \cdot A(C_j - C_{j-1})}{\Delta x_m} \left( h_{fg} + c_{pv} \frac{T_{j+1} + T_j}{2} \right) \]

\[
\frac{2 \lambda_m \lambda_{m+1} A(T_j - T_{j-1})}{\Delta x_m} + \frac{D_{\text{vm eff}} \cdot \varepsilon_m \cdot A(C_j - C_{j-1})}{\Delta x_m} \left( h_{fg} + c_{pv} \frac{T_{j+1} + T_j}{2} \right)
\]

\[
\frac{\partial C_j}{\partial t} = \frac{2 \varepsilon_m \varepsilon_{m+1} D_{\text{vm eff}} \cdot D_{\text{vm+1 eff}} (C_{j+1} - C_j)}{\Delta x_m (\alpha_{m+1} D_{\text{vm+1 eff}} \cdot \Delta x_m + \varepsilon_{m+1} D_{\text{vm eff}} \cdot \Delta x_m + 2 \lambda_m \lambda_{m+1} R_{\text{m+1/m}})}
\]

\[
+ \frac{\rho_{hm} \left[ k \left( M_{C_j} - M_{C_{j-1}} \right) - B \right]}{\varepsilon_m \Delta x^2_m} D_{\text{vm eff}} (C_j - C_{j-1})
\]

\[
\frac{\partial Q_j}{\partial t} = \frac{2 \lambda_m \lambda_{m+1} A(T_j - T_{j-1})}{\Delta x_m + \frac{2 \lambda_m \lambda_{m+1} R_{\text{m+1/m}}}{\Delta x_m}} + \frac{D_{\text{vm eff}} \cdot \varepsilon_m \cdot A(C_j - C_{j-1})}{\Delta x_m} \left( h_{fg} + c_{pv} \frac{T_{j+1} + T_j}{2} \right)
\]

\[
= \frac{2 \lambda_m \lambda_{m+1} A(T_j - T_{j-1})}{\Delta x_m + \frac{2 \lambda_m \lambda_{m+1} R_{\text{m+1/m}}}{\Delta x_m}} + \frac{D_{\text{vm eff}} \cdot \varepsilon_m \cdot A(C_j - C_{j-1})}{\Delta x_m} \left( h_{fg} + c_{pv} \frac{T_{j+1} + T_j}{2} \right)
\]

\[
\frac{\partial Q_j}{\partial t} = \frac{2 \lambda_m \lambda_{m+1} A(T_j - T_{j-1})}{\Delta x_m + \frac{2 \lambda_m \lambda_{m+1} R_{\text{m+1/m}}}{\Delta x_m}} + \frac{D_{\text{vm eff}} \cdot \varepsilon_m \cdot A(C_j - C_{j-1})}{\Delta x_m} \left( h_{fg} + c_{pv} \frac{T_{j+1} + T_j}{2} \right)
\]

\[
\frac{\partial C_j}{\partial t} = \frac{2 \lambda_m \lambda_{m+1} A(T_j - T_{j-1})}{\Delta x_m + \frac{2 \lambda_m \lambda_{m+1} R_{\text{m+1/m}}}{\Delta x_m}} + \frac{D_{\text{vm eff}} \cdot \varepsilon_m \cdot A(C_j - C_{j-1})}{\Delta x_m} \left( h_{fg} + c_{pv} \frac{T_{j+1} + T_j}{2} \right)
\]

\[
\frac{\partial Q_j}{\partial t} = \frac{2 \lambda_m \lambda_{m+1} A(T_j - T_{j-1})}{\Delta x_m + \frac{2 \lambda_m \lambda_{m+1} R_{\text{m+1/m}}}{\Delta x_m}} + \frac{D_{\text{vm eff}} \cdot \varepsilon_m \cdot A(C_j - C_{j-1})}{\Delta x_m} \left( h_{fg} + c_{pv} \frac{T_{j+1} + T_j}{2} \right)
\]

\[
\frac{\partial Q_j}{\partial t} = \frac{2 \lambda_m \lambda_{m+1} A(T_j - T_{j-1})}{\Delta x_m + \frac{2 \lambda_m \lambda_{m+1} R_{\text{m+1/m}}}{\Delta x_m}} + \frac{D_{\text{vm eff}} \cdot \varepsilon_m \cdot A(C_j - C_{j-1})}{\Delta x_m} \left( h_{fg} + c_{pv} \frac{T_{j+1} + T_j}{2} \right)
\]

\[
\frac{\partial Q_j}{\partial t} = \frac{2 \lambda_m \lambda_{m+1} A(T_j - T_{j-1})}{\Delta x_m + \frac{2 \lambda_m \lambda_{m+1} R_{\text{m+1/m}}}{\Delta x_m}} + \frac{D_{\text{vm eff}} \cdot \varepsilon_m \cdot A(C_j - C_{j-1})}{\Delta x_m} \left( h_{fg} + c_{pv} \frac{T_{j+1} + T_j}{2} \right)
\]
The moisture balance for the nodes was given by:

$$\frac{\partial C_j}{\partial t} = \frac{D_{vm, eff} (C_{j+1} - C_j)}{\Delta x_m^2} + \rho_{bm} \frac{k (MC_j - MC_{ej}) - B}{\varepsilon_m}$$

$$- 2 \varepsilon_{m,1} \frac{D_{vm,1, eff} \cdot D_{vm, eff} (C_j - C_{j-1})}{\Delta x_m \left( \varepsilon_{m,1} \cdot D_{vm,1, eff} \cdot \Delta x_m + \varepsilon_m \cdot D_{vm, eff} \cdot \Delta x_{m-1} + 2 R_{MTm-1/m} \cdot \varepsilon_{m,1} \cdot \varepsilon_m \cdot D_{vm,1, eff} \cdot D_{vm, eff} \right)}$$

At node $j = J+K+L+1$:

$$T = T_{gr}$$

and

$$\frac{\partial C_{J+K+L+1}}{\partial t} = \rho_{bm} \frac{k (MC_{J+K+L+1} - MC_{e,J+K+L+1}) - B}{\varepsilon_m} \frac{D_{vm, eff} (C_{J+K+L+1} - C_{J+K+L})}{\Delta x_m^2}$$

(34)

The initial amount of energy contained within the top node ($j = 1$) was given by:

$$Q_i = (1 - \varepsilon_m) \rho_m A \frac{\Delta x}{2} c_{pm} T_i + MC_i (1 - \varepsilon_m) \rho_p A \frac{\Delta x}{2} c_{pm} T_i + \varepsilon_p \rho_p A \frac{\Delta x}{2} c_{pm} T_i + C_i \varepsilon_p A \frac{\Delta x}{2} h_{fg}$$

... (37)

and for all other nodes ($2 \leq j \leq J+K+L+1$) by:

$$Q_j = T_j \left[ (1 - \varepsilon_m) \rho_m A \Delta x_i c_{pm} + (1 - \varepsilon_m) \rho_p A \Delta x_i c_{pm} MC_i + \varepsilon_m \rho_m A \Delta x_i c_{pm} + \varepsilon_p A \Delta x_i c_{pm} + C_i \varepsilon_p A \Delta x_i h_{fg} \right] + C_i \varepsilon_p A \Delta x_i h_{fg}$$

(38)

The model formulation also relied on the following ancillary equations based on ideal gas laws (ASHRAE, 1993):

$$P_v = \frac{C.R (T + 273.15)}{0.018}$$

(39)

Therefore,

$$RH = \frac{P_v}{P_{ys}} = \frac{C.R (T + 273.15)}{0.018 P_{ys} (T)}$$

(40)
\[ C = \frac{0.018 RH_u P_v \phi (T)}{R (T + 273.15)} \]  

and

\[ P_v = e^{\frac{23.4795 \cdot 3900.56}{T + 233.833}} \]  

(41)

(42)

2.5 Numerical solution

Matlab version 7.1.0.246 (R14) with default value of 0.001 of relative error tolerance and “ode 2.3” solver was used to solve the model numerically. Before proceeding to the final solutions, the model was checked in order to verify that it was being solved with acceptable numerical accuracy. This was done by checking the levels of changes in the solutions when the number of space steps, the relative tolerance of the Matlab solver, the depth of soil affected by the drying and the number of space steps in the material below the rice grain bed were all changed. Values that gave acceptably small changes in the predictions were chosen for these variables. The model was then checked against analytical solutions for simplified versions of the model, such as for heat conduction through an infinite slab and mass transfer through an infinite slab. The numerical solution exactly matched the analytical solutions in every case, confirming that the equations being used were good approximations for the simplified system.

Fig 4: Measured ambient temperature for Dec 22 2004

Fig 5: Measured relative humidity of ambient air for Dec 22, 2004.
2.6 Input variables

The input variables and the range of the values used presented in Appendix A. Measured input parameters such as ambient air temperature and humidity, that varied during the day had polynomial equations fitted with time as the independent variable so that a close estimate of the variable could be easily estimated within the model. Figures 3, 4 and 5 show examples of the solar radiation, ambient air temperature and relative humidity plots with fitted equations used.

2.7 Model validation

The model was validated by testing its predictions against the experimental data collected by the extensive monitoring of 8 drying trials within a larger factorial design on the effects of solar drying of rice in beds (Meas et al. 2011) and against four other extensively monitored drying trials from previous work (Meas 2006). This was done to identify the reliability of the model predictions and to find out the reasons for any lack of fit between the predicted and experimental data. Any lack of fit may be attributed to one or more of the following (Bahnasawy and Shenana, 2004):

- Inappropriate formulation of the model or the formulated model has some weakness, (e.g. important mechanisms ignored)
- Uncertainty in the values of the system inputs, or
- Uncertainty in the experimental data.

The model can be deemed adequate if the differences between the measured and predicted results can be explained by the later two aspects.

A sensitivity analysis was carried out for some trials to identify the sensitivity of the model to the ranges of the system inputs identified in order to access the importance of the second aspect.

3. RESULTS

Only some of the experimental/prediction comparisons will be used to demonstrate the validation of the model.

3.1 Drying time

The drying time required to bring the grain to the target moisture content (MC) of 14%, was predicted by the model using the best estimates of the system input
parameters and these are compared with the measured drying times in Figures 6 to Fig 8. These figures show the same data, but with different parameters highlighted to show the effects of the differences in the key parameters of rice type, bed depth, stirring, covering and the type of pad the rice was dried on. On average, the model under-predicted the drying times by about 40 minutes (between about 3% and 12%) for total drying times between 340 and 1420 minutes.

Fig 6 indicates the effect of rice variety and bed depth. The model predicted the drying time for the two varieties and bed depths equally well. An average of 800 min was predicted for the Pka Knhey variety which was about 20 min longer than for CAR11 variety. Drying with a 2 cm bed depth was predicted to take 670 min on average which was 50 min shorter than the 3 cm depth bed. These trends were consistent with the measured drying times.

![Graph showing measured vs predicted drying times for different rice varieties and bed depths.](image)

**Fig 6: Comparison of the measured and predicted drying times (variety and depth)**

Fig 7 shows the same data, but plotted with stirring and covering treatments indicated. The beds that were stirred and exposed to the sun for the whole time were predicted to reach the target MC in the shortest time (455 min).
Next were the beds that were not stirred and not covered (776 min) and stirred and covered (882 min). The longest time was predicted for the beds that were not stirred but covered (1063 min). All of these indicate that stirring helped shorten the drying while covering and shading prolonged the drying time.

![Graph showing comparison of measured and predicted drying times.](image)

Fig 7: Comparison of the measured and predicted drying times: (stirring and covering methods)

While the drying time was different for each stirring, shading and covering treatment, the predictions were similarly accurate for all, suggesting that the model was equally accurate irrespective of the heat and mass transfer mechanisms.

Fig 8 plots the same data but with the pad type identified. Table 1 gives the average drying time for each pad type. Overall, the model predictions of drying time were consistent with the measured data but were consistently lower for the trials with a polystyrene pad except for the treatments that took 600 minutes to dry. The drying on the tarpaulin spread on polystyrene gave the
shortest drying time (502 min) when averaged over all treatments and had the largest difference (~20%) between predicted and measured (predictions too short). The under-prediction of the drying time was due to the over prediction of the temperature. The poorer predictions for polystyrene pads were analysed but no obvious reason was identified especially in terms of the input parameter values. It is speculated that the solar intensity data may have been over estimated.

![Graph showing comparison of measured and predicted drying times](image_url)

Fig 8: Comparison of the measured and predicted drying times (drying pads)

| Table 1: Average measured and predicted drying times for individual drying pads, min |
|--------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Net on husk | Mat on soil | Net on soil | Tarpaulin on soil | Tarpaulin on polystyrene |
| Measured | 665 | 848 | 919 | 930 | 602 |
| Predicted | 659 | 804 | 855 | 858 | 502 |
3.2 Temperature

On the whole, the predicted temperatures for different layers of the bed as a function of time are in higher than the measured values but are in reasonable agreement in terms of following the mean trends shown in Fig 9 to 11. Temperature is affected very strongly by the change in the solar intensity as can be seen by looking at the shape of Fig 3 with that of Fig 9 which is data for the same day. In most cases, the lack of fit can be explained by uncertainties in the values of the system inputs used, such as the smoothing effect by fitting a polynomial equation to the measured solar radiation values, ambient temperature and relative humidity data and uncertainties in the experimental data.

Figure 10 shows the effect of covering the bed was predicted well and both Figures 10 and 11 show that the effect of stirring was also modelled adequately for prediction purposes.

For the case of drying on the polystyrene slabs (Fig 11), the temperatures were over predicted by more than for other pads and this could not be explained by the sensitivity analysis or data uncertainty. No logical reason for this over prediction of temperature was identified, but it is speculated that the solar intensity was over estimated.

3.3 Moisture content

Fig 12 to 14 show a comparison of the predicted with the measured MCs. The measured MCs were considered particularly uncertain due to the indirect method of the moisture meter employed and the difficulty in getting appropriate grain samples from different parts of the bed. Therefore, rather than comparing the MC at each location in the bed, predictions for the average MC of the bed are shown.

The measured MCs are scattered around the model predictions. Again, uncertainty in the system input values and experimental measurements could explain most of the lack of fit. Irregular changes in the MCs measured during the experiments confirm that significant uncertainties existed in the measurements. With the moisture meter used, about 200 g of the grain sample was needed for every moisture determination. For that reason, even when extreme attention was paid in the sampling process, the reading from the meter could easily fail to accurately represent the MC of the grain at the exact position intended. Moreover, the meter error was ±1% MC.

Despite these uncertainties, the main features of the changes in moisture content of the grain during drying were described by the model as shown in Fig 12 where there was continuous drying with no intervention, compared to Fig 13 where the effect of covering and stirring can be seen. The effect of the over
prediction of temperature when on a polystyrene base, results in the over prediction on the amount of drying as shown in Fig 14.

Fig 9: Comparison of the predicted and measured temperatures for Pka Knhey, 2 cm, mat spread on soil, no stirring, no covering, Day One (Dec 22, 2004) Notes: Pred: Predicted; Meas: Measured; T1, T7, T13, T19 and T25: Temperatures at nodes 1 (the bed surface), 7, 13 (middle of the bed), 19 and 25 (bottom of the bed), respectively. (NCT are the Hycal RH probes, IB are the I Button sensors and Therm are the thermocouples)
Fig 10: Comparison of the predicted and measured temperatures for Pka Knhey, 2 cm, mat spread on soil, stirring, covering plus shading, Day One (Dec 18, 2004)

Notes: Pred: Predicted; Meas: Measured; T1, T7, T13, T19 and T25: Temperatures at nodes 1 (the bed surface), 7, 13 (middle of the bed), 19 and 25 (bottom of the bed), respectively. (NCT are the Hycal RH probes, IB are the I Button sensors and Therm are the thermocouples)
Fig 11: Comparison of the predicted and measured temperatures for CAR11, 2 cm, tarpaulin spread on polystyrene, stirring, no covering, Day One (Dec 11, 2004)

Notes: Pred: Predicted; Meas: Measured; T1, T7, T13, T19 and T25: Temperatures at nodes 1 (the bed surface), 7, 13 (middle of the bed), 19 and 25 (bottom of the bed), respectively. (NCT are the Hycal RH probes, IB are the I Button sensors and Therm are the thermocouples)
Fig 12: Comparison of the predicted and measured MCs for Pka Knhey, 2 cm, mat spread on soil, no stirring, no covering, Day One (Dec 22, 2004)

Notes: Pred: Predicted; Meas: Measured; MC1-13, MC7-19, MC13-25, MC1-25: Moisture contents at nodes 1 to 13 (upper half of the bed), 7 to 19 (middle portion of the bed), 13 to 25 (lower half of the bed, and 1 to 25 (whole bed), respectively
Fig 13: Comparison of the predicted and measured MCs for Pka Knhey, 2 cm, mat spread on soil, stirring, covering plus shading, Day One (Dec 18, 2004)

Notes: Pred: Predicted; Meas: Measured; MC1-13, MC7-19, MC13-25, MC1-25: Moisture contents at nodes 1 to 13 (upper half of the bed), 7 to 19 (middle portion of the bed), 13 to 25 (lower half of the bed, and 1 to 25 (whole bed), respectively
3.4 Water Activity (bed air $RH$)

The water activities predicted by the model were consistently lower than measured (Fig 15-17) and hence the rate of drying is over-predicted. Apart from the uncertainties in the values of the system inputs, there were significant uncertainties in the measured $RH$ data especially for the middle and bottom layers. The water activities measured for these two layers were in some cases higher than 1 (the maximum possible value). A possible reason is that the Hycal probes became wet by the free and condensing water within the bed, thereby...
affecting their calibration. Despite these problems with measurement, the model has not predicted the experimental water activities consistently, although the trends in the data are predicted. Another possible reason is that the assumption of equilibrium between the bed water activity and the kernel surface MC is not appropriate. The water activity offset is also a potential consequence of the over prediction of the internal bed temperatures noted above. More work is needed to investigate why the model and experiments do not agree more closely.

![Graph showing water activity over time](image)

Fig 15: Comparison of the predicted and measured water activities for Pka Knhey, 2 cm, mat spread on soil, no stirring, no covering, Day One (Dec 22, 2004)

Notes: Pred: Predicted; Meas: Measured; Aw1, Aw7, Aw13, Aw19, and Aw25: Water activities at nodes 1, 7, 13, 19 and 25, respectively
Fig 16: Comparison of the predicted and measured water activities for Pka Knhey, 3 cm, mat spread on soil, no stirring, covering plus shading, Day One (Dec 18, 2004)

Notes: Pred: Predicted; Meas: Measured; Aw1, Aw7, Aw13, Aw19, and Aw25: Water activities at nodes 1, 7, 13, 19 and 25, respectively
Fig 17: Comparison of the predicted and measured water activities for CAR11, 2 cm, tarpaulin spread on polystyrene, stirring, no covering, Day One (Dec 11, 2004)

Notes: Pred: Predicted; Meas: Measured; Aw1, Aw7, Aw13, Aw19, and Aw25: Water activities at nodes 1, 7, 13, 19 and 25, respectively

4. CONCLUSIONS

A mathematical model for heat and moisture transport within bed of solar drying rice was developed to investigate the conditions of the grain and the air at different bed layers during the drying process.

The predicted drying time, temperatures and moisture contents were found to compare reasonably well with the experimental data except when a polystyrene pad was used. However, the model on average did predict drying times about 40 minutes (3-12%) shorter than they were measured, consistently over predicted the bed temperatures, and did not predict the experimental water activities consistently. Uncertainty in the data measured and used for the model parameters
and the experimental methods accounted for most of the difference between predicted and measured data.

Overall, the model proved to be a good mechanistic tool for the design and management of the solar drying system with advantages of simplicity and practical accuracy. Furthermore the effect of the experimental variables in controlling the drying rate is well predicted.

5. NOMENCLATURE

Latin symbols

\begin{itemize}
  \item \( A \) Flat surface area of drying bed \( \text{m}^2 \)
  \item \( A_{\text{top}} \) Top surface area of drying bed \( \text{m}^2 \)
  \item \( a_k \) Specific surface area of paddy kernels (surface/ bulk volume) \( \text{m}^2/\text{m}^3 \)
  \item \( B \) The second coefficient for drying constant \( 1/\text{s} \)
  \item \( C \) Moisture concentration in air \( \text{kg}/\text{m}^3 \) of air
  \item \( C_a \) Moisture concentration in the ambient air \( \text{kg}/\text{m}^3 \) of air
  \item \( c_p \) Specific heat capacity \( (a, \text{carb, h, m, mat, p, pdr, pol, s, v, and w} \) for ambient air, carbohydrate, husk, a material, mat, paddy, paddy dry matter, polystyrene, soil, water vapour and water, respectively) \( \text{J}/\text{kg}.^\circ\text{C} \)
  \item \( D_v \) Diffusivity of water vapour \( (a, m \) and \( p \) in open air, exposed material and in grain bed, respectively) \( \text{m}^2/\text{s} \)
  \item \( D_{\text{vm.eff}} \) Effective diffusivity of the water vapour in the materials 2 and 3 \( \text{m}^2/\text{s} \)
  \item \( d_k \) Thickness of paddy kernel \( \text{mm} \)
  \item \( F_{A1} \) Configuration or geometric factor between shading tarpaulin and covering tarpaulin or between shading tarpaulin and grain bed
  \item \( F_{A2} \) Configuration or geometric factor between covering tarpaulin and grain bed
  \item \( h \) Convective heat transfer coefficient \( \text{W}/\text{m}^2.^\circ\text{C} \)
  \item \( h_{\text{fg}} \) Latent heat of evaporation (from fluid to gas) \( \text{J}/\text{kg} \)
  \item \( h_g \) Enthalpy or heat of evaporation \( \text{J}/\text{kg} \)
  \item \( h_{\text{gin}} \) Enthalpy or heat for evaporating moisture into a node \( \text{J}/\text{kg} \)
  \item \( h_{\text{gout}} \) Enthalpy or heat for evaporating moisture out from a node \( \text{J}/\text{kg} \)
  \item \( I \) Solar intensity \( \text{W}/\text{m}^2 \)
  \item \( I_{sh} \) Solar intensity from the shade \( \text{W}/\text{m}^2 \)
  \item \( i \) Counter with time
  \item \( J \) Number of space steps in the grain bed
  \item \( j \) Node number
  \item \( K \) Number of space steps in material 2
  \item \( k \) The first coefficient for drying constant \( 1/\text{s} \)
\end{itemize}
Convective moisture transfer coefficient \( m/s \)
Number of space steps in material 3

Thickness of air layer below covering tarpaulin \( m \)
Thickness or depth of a material \( m \)
Depth of the grain bed \( m \)
Depth of soil affected by drying \( m \)
Moisture content \( \text{MC} \) \((\text{db, es, ws, meas, and pred for dry basis, equilibrium, initial, wet basis, measured and predicted, respectively}) \) \% or decimal
Slope of moisture isotherm
Water vapour pressure \( \text{Pa} \)
Saturated water vapour pressure \( \text{Pa} \)
Total pressure \( \text{Pa} \)
Heat \( J \)
Ideal gas constant, 8.3145 \( J/\text{mol K} \)
Resistance for heat conducted from covering tarpaulin to paddy bed \( m^2.\circ C/W \)
Resistance for the mass transfer due to the interface \( m^2.\circ C/W \)
Relative humidity \( \% \) or decimal
Relative humidity \( (a \text{ and } i, \text{ for the ambient air and initial, respectively}) \) \% or decimal
Switches \( (1 \text{ and } 2 \text{ for shading and covering, respectively}) \)
Temperature \( (a, \text{ cov, } \text{cryst, } g, \text{ gr, } h, \text{ i, m, mats, meas, mels, p, pol, pred, s, sh, sky and stir for ambient air, covering tarpaulin, crystallisation, glass transition, ground, husk, initial, a material, mat, measured, melting, paddy, polystyrene, predicted, soil, shading tarpaulin, sky and stirring, respectively}) \) \( ^\circ C \)
Time \( (\text{for stirring}) \) \( s \)
Reciprocal of \( R_{\text{tarp/p}} \) \( W/m^2.\circ C \)
Volume of top layer of grain \( m^3 \)
Spatial coordinate \( m \)

Absorptivity of a surface \( \text{tarp and p for the tarpaulin and grain bed, respectively}) \)
Spatial step \( (2, 3, m \text{ and p for material 2, material 3, a material and the grain bed, respectively}) \)
Porosity of air in a bulk material \( (h, m, mats, p, pol \text{ and s for the husk, a material, mat, paddy, polystyrene and soil, respectively}) \)
Emissivity of a surface \( \text{tarp and p for the tarpaulin and grain} \)

\[ \beta \]

\[ \Delta x \]

\[ \varepsilon \]

\[ \varepsilon \]


\[ \lambda_a \]
Thermal conductivity of the air \( \text{W/m.}^\circ\text{C} \)

\[ \lambda \]
Effective thermal conductivity (\( h, m, m_a, p, p_o, s \) and \( \text{tarp} \) for husk, material, mat, paddy, polystyrene, soil and tarpaulin, respectively) \( \text{W/m.}^\circ\text{C} \)

\[ \rho \]
True density (\( a, h, m, m_a, p, p_o, s \) for ambient air, husk, a material, mat, paddy, polystyrene and soil, respectively) \( \text{kg/m}^3 \)

\[ \rho_b \]
Bulk density (\( a, h, m, m_a, p, p_o, s \) for ambient air, husk, a material, mat, paddy, polystyrene and soil, respectively) \( \text{kg/m}^3 \)

\[ \sigma \]
Stefan-Boltzmann constant, \( 5.669 \times 10^{-8} \text{W/m}^2\text{.K}^4 \)

**APPENDIX A: Summary of the values and ranges of the system inputs used**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value used</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_k ) ( [\text{m}^2/\text{m}^3] )</td>
<td>Specific surface area of CAR11</td>
<td>1000 ± 200</td>
<td>Mohsenin (1986)</td>
</tr>
<tr>
<td>( a_k ) ( [\text{m}^2/\text{m}^3] )</td>
<td>Specific surface area of Pka Knhey</td>
<td>1100 ± 240</td>
<td>Mohsenin (1986)</td>
</tr>
<tr>
<td>( A ) ( [\text{m}^2] )</td>
<td>Flat surface area of the bed</td>
<td>1</td>
<td>Assumption</td>
</tr>
<tr>
<td>( c_{pa} ) ( [\text{J/kg.}^\circ\text{C}] )</td>
<td>Specific heat of air</td>
<td>1007</td>
<td>Brooker et al (1992), Incropera and DeWitt, (1996) and Lienhard and Lienhard (2005)</td>
</tr>
<tr>
<td>( c_{ph} ) ( [\text{J/kg.}^\circ\text{C}] )</td>
<td>Specific heat of the husk</td>
<td>1870 ± 187</td>
<td>Urbicain and Lozano (1997)</td>
</tr>
<tr>
<td>( c_{pmat} ) ( [\text{J/kg.}^\circ\text{C}] )</td>
<td>Specific heat of the mat</td>
<td>1340 ± 134</td>
<td>Incropera and DeWitt, (1996)</td>
</tr>
<tr>
<td>( c_{pp} ) ( [\text{J/kg.}^\circ\text{C}] )</td>
<td>Specific heat of the grain dry matter</td>
<td>1115 ± 75</td>
<td>Own estimation</td>
</tr>
<tr>
<td>( c_{ppol} ) ( [\text{J/kg.}^\circ\text{C}] )</td>
<td>Specific heat of the polystyrene</td>
<td>1210</td>
<td>Incropera and DeWitt, (1996)</td>
</tr>
<tr>
<td>( c_{pso} ) ( [\text{J/kg.}^\circ\text{C}] )</td>
<td>Specific heat of the soil</td>
<td>1870 ± 30</td>
<td>Incropera and DeWitt (1996), Çengel (1997), Çengel (2003)</td>
</tr>
<tr>
<td>( c_{pv} ) ( [\text{J/kg.}^\circ\text{C}] )</td>
<td>Specific heat of water vapour</td>
<td>1875</td>
<td>Brooker et al. (1992), Incropera and DeWitt (1996)</td>
</tr>
<tr>
<td>Parameter</td>
<td>Description</td>
<td>Value</td>
<td>Source</td>
</tr>
<tr>
<td>-----------</td>
<td>-------------</td>
<td>-------</td>
<td>--------</td>
</tr>
<tr>
<td>$c_{pw}$</td>
<td>Specific heat of water</td>
<td>4183</td>
<td>Incropera and DeWitt (1996), Lienhard and Lienhard (2005)</td>
</tr>
<tr>
<td>$d_k$</td>
<td>Thickness of CAR11 kernel</td>
<td>2.12 ± 0.16</td>
<td>Own measurement</td>
</tr>
<tr>
<td>$d_k$</td>
<td>Thickness of Pka Knhey kernel</td>
<td>1.96 ± 0.18</td>
<td>Own measurement</td>
</tr>
<tr>
<td>$h$</td>
<td>Convective heat transfer coefficient</td>
<td>Dependent on wind speed</td>
<td>Table 6.1, Meas (2006)</td>
</tr>
<tr>
<td>$h_{fg}$</td>
<td>Latent heat of evaporation</td>
<td>$2424.5 \pm 164.5$</td>
<td>Brooker et al. (1992), Incropera and DeWitt (1996), Jain and Tiwari (2004), Lienhard and Lienhard (2005)</td>
</tr>
<tr>
<td>$I$</td>
<td>Solar intensity</td>
<td>Dependent on cloud movement</td>
<td>Table 6.2, Meas (2006)</td>
</tr>
<tr>
<td>$L_d$</td>
<td>Thickness of the air gap above and below the bed</td>
<td>1 ± 0.2</td>
<td>Assumption</td>
</tr>
<tr>
<td>$L_h$</td>
<td>Thickness of the husk</td>
<td>70 ± 5</td>
<td>Own measurement</td>
</tr>
<tr>
<td>$L_{mat}$</td>
<td>Thickness of the mat</td>
<td>2 ± 0.5</td>
<td>Own measurement</td>
</tr>
<tr>
<td>$L_p$</td>
<td>Depth or thickness of the grain bed</td>
<td>$20 \pm 2$ and $30 \pm 2$</td>
<td>Own measurement</td>
</tr>
<tr>
<td>$L_{pol}$</td>
<td>Thickness of polystyrene</td>
<td>40 ± 2</td>
<td>Own measurement</td>
</tr>
<tr>
<td>$L_{tarp}$</td>
<td>Thickness of the tarpaulin</td>
<td>0.6 ± 0.1</td>
<td>Own measurement</td>
</tr>
<tr>
<td>$MC_{ip}$</td>
<td>Initial moisture content of the grain</td>
<td>0.266 to 0.292</td>
<td>Own measurement</td>
</tr>
<tr>
<td>$MC_{im}$</td>
<td>Initial moisture content of materials 2 and 3</td>
<td>0</td>
<td>Assumption</td>
</tr>
<tr>
<td>$R_{MT/m+1}$</td>
<td>Resistance to moisture transfer through tarpaulin</td>
<td>$\infty$</td>
<td>Assumption</td>
</tr>
<tr>
<td>$R_{MT/m+1}$</td>
<td>Resistance to moisture transfer through nylon net and mat</td>
<td>0</td>
<td>Assumption</td>
</tr>
<tr>
<td>$RH_a$</td>
<td>Ambient air relative humidity</td>
<td>Fluctuated</td>
<td>Table 6.3, Meas (2006)</td>
</tr>
<tr>
<td>$T_a$</td>
<td>Ambient air temperature</td>
<td>Fluctuated</td>
<td>Table 6.4, Meas (2006)</td>
</tr>
</tbody>
</table>
REFERENCES


