SIMULATION OF THE MIXED-MODE NATURAL-CONVECTION SOLAR DRYING OF MAIZE

I. N. Simate

Department of Agricultural Engineering, University of Zambia, P.O. Box 32379, Lusaka, Zambia

ABSTRACT

A mathematical model for mixed mode natural convection solar drying of maize grain is presented. The drying is described by a deep bed procedure that includes conduction within the grain bed. The conduction is due to radiative energy falling on the upper surface of the bed. The results show that temperatures at the top and bottom of the bed are higher than that in the middle resulting in two drying fronts one at the top and the other at the bottom of the bed and moving in opposite directions. This results in more uniform moisture content distribution than in an indirect dryer. The results are verified against experimental data from a prototype mixed mode natural convection maize solar dryer. The laboratory solar dryer was constructed at Newcastle University, U.K. and the experiments carried out under a solar simulator. The agreement between theory and experiment is very good.

Key Words: Conduction; Convection; Deep bed; Drying front; Mixed mode solar dryer

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INTRODUCTION

The method of collecting solar energy and transferring it to the product is used to identify the type of solar dryer as direct, indirect and mixed type (Bala and Woods, 1994).

In the direct solar dryer, the grains absorb direct sun radiation that passes through a transparent cover or side panels. Evaporation takes place principally from the top layer grains which also conduct the absorbed heat to the bottom grains.

Indirect dryers have a separate compartment, viz. the collector, in which the air from the ambient passes through and is heated before entering the grain bed. The hot air performs two functions; it supplies the necessary heat to evaporate moisture from the grain as well as carry away the evaporated moisture.

Mixed-mode type of dryer combines the features of both the direct and indirect types of dryers. The grain is therefore dried by a combination of both direct radiation with conduction from the top layer grains to the bottom layers and convection of hot air from the collector entering the bottom layers and moving to the top layers.

Performance studies of mixed-mode solar dryers have been reported in the works of Garba et al. (1990). These investigators compared them with other types of dryers and reported that the mixed-mode dryers give higher drying rates. These works, however, do not include simulation of the mixed-mode solar dryers.

Garg and Sharma (1990) have presented a mathematical model of a mixed-mode solar dryer and considered the drying material as a thin bed. In their model, the radiation absorbed by the drying material was taken as equal to the product of the absorptivity of the drying material, the transmissivity of the glass cover and the solar incidence radiation. This term was added to the energy transferred by convection from air to the drying material so that the total energy for drying was increased. However, the theory and simulation of the mixed-mode solar dryer, combining convection and conduction in a deep bed has not yet been examined.

In this study, the radiation falling on the grain at the top of the bed through the transparent dryer cover and the downward conduction of heat from grain at the top to that at the bottom of the bed are incorporated in the deep bed drying model.

Bala and Woods (1994) introduced the deep bed analysis to the simulation of indirect natural convection solar dryers. This has paved the way for the modelling of the complex mixed-mode solar dryer to be studied.

The objective of this paper is to develop a computer simulation model for the mixed-mode solar drying process with the application of the deep
bed theory combined with radiation at the upper surface and conduction in the grain bed.

MATHEMATICAL MODEL

The system configuration is shown in Figure 1. In this configuration, the dryer width is the same as the collector width. Airflow through the dryer is driven by buoyancy pressure created in: (a) the single covered collector with flow over the absorber, (b) the space below the grain bed, (c) the grain bed and (d) the space above the grain bed.

Deep Bed Drying

Simate (1999) has described in detail the simulation of deep bed with downward conduction employed here.

Mass balance equation is obtained by equating the moisture leaving the grain to the moisture entering the air-stream by convection:

\[
\rho_g \frac{\partial M}{\partial t} = -G \frac{\partial H}{\partial X}
\]

(1)

For the rate of change of moisture content, it is assumed that the grain dries in thin layers. In this analysis the Page equation, given by Brooker et al.
(1992) is used:

\[
\frac{M_t - M_e}{M_0 - M_e} = \exp\left(-Kt^C\right) \quad (2)
\]

Misra and Brooker (1980) determined the drying constants for maize for the ranges of \(RH = 3\) to 83\%, \(\theta = 2.2\) to 71.1\(^\circ\)C, \(V = 0.025\) to 2.33 m/s and \(M_0 = 0.18\) to 0.6 kg/kg dry basis as:

\[
K = \exp\left(-7.1735 + 1.2793 \ln(1.8\theta + 32.0) + 0.1378V\right) \quad (3)
\]

\[
C = 0.0811 \ln(100RH) + 0.78M_0 \quad (4)
\]

The equilibrium moisture content \(M_e\), is calculated by using the Chung-Pfost equation taken from the ASAE Standards (1991) and is given by:

\[
M_e = 0.33872 - 0.05897 \ln\left(-\left(\theta + 30.205\right)\ln(RH)\right) \quad (5)
\]

The rate of heat transfer equation for the interior of the bed describes that the change in enthalpy of grain with time is the sum of the energy to heat grain by conduction and convection and the energy lost by grain through evaporation of moisture and is given as:

\[
\rho_e \left(C_{pg} + C_M M\right) \frac{\partial\theta}{\partial t} = \frac{\partial}{\partial X} \left(k_g \frac{\partial\theta}{\partial X}\right) + a_V h_S (T - \theta) + h_{fg} \rho_e \left(\frac{\partial M}{\partial t}\right) \quad (6)
\]

where \(h_S\) is the convective heat transfer coefficient, and is given by Brooker et al. (1992):

\[
h_S = 0.9918 C_{pg} G \left(\frac{d_x G}{\mu_d}\right)^{-0.34} \quad (7)
\]

The specific heat capacity of maize grain \(C_{pg}\), is given by the ASAE Standards (1991) as:

\[
C_{pg} = 1465 + 3560M_{w.b.} \quad (8)
\]

where \(M_{w.b.}\) is the moisture content.

The heat of vaporisation of water in the maize grain \(h_{fg}\), is given by Brooker et al. (1992) as:

\[
h_{fg} = (250200 + 2390\theta)[1 + 1.2925 \exp(-16.961M)] \quad (9)
\]
The thermal conductivity of the maize grain \( k_g \), was obtained from the ASAE Standards (1991) and is given by:

\[
k_g = 0.1409 + 0.112M_w, \tag{10}
\]

The equation for exchange of energy between air and grain describes that the change in enthalpy of air across a layer of grain is the sum of energy to increase temperature of moisture lost by grain and the energy to heat grain by convective heat transfer. It is given as:

\[
G(C_{pa} + C_{ph}) \frac{\partial T}{\partial X} = \rho_g C_{ph}(T - \theta) \frac{\partial M}{\partial t} - a_v h_s(T - \theta) \tag{11}
\]

The boundary condition equation at the bottom of the bed describes that the energy accumulated in the bottom layer of grain is the sum of energy gained by conduction from the upper layer and the energy gained by convection from air from collector and the energy released due to moisture evaporation. It is given as:

\[
(C_{pg} + C_{pl}M)\rho_g \frac{\partial \theta}{\partial t} = \left( \frac{1}{\delta X} \right) k_g \frac{\partial \theta}{\partial X} + a_v h_s(T - \theta) + h_{fg} \rho_g \frac{\partial M}{\partial t} \tag{12}
\]

The boundary condition equation at the top of the bed describes that the energy accumulated in the top layer of grain is the sum of the radiant energy absorbed by the bed surface and the energy lost by the grain surface to the drying chamber cover by radiation and the energy transferred by conduction into the interior of the bed and the energy lost by the grain surface to the air from the interior of the bed by convection and the energy lost due to heat of vaporisation. It is given as:

\[
(C_{pg} + C_{pl}M)\rho_g (\delta X) \frac{\partial \theta}{\partial t} = \frac{a_g S \tau_c S}{1 - \rho_g \lambda_S \rho_c S} \phi - h_{rg}(\theta - T_{cD}) - k_g \frac{\partial \theta}{\partial X} \]

\[
- (\delta X) a_v h_s(T - \theta) + h_{f_g} \rho_g (\delta X) \frac{\partial M}{\partial t} \tag{13}
\]

where the radiative heat transfer coefficient from maize grain to the drying chamber cover \( h_{rg} \) is given by Eqn.(17) with \( T_p \), \( T_c \) and \( \epsilon_{pl} \) replaced by \( \theta \), \( T_{cD} \) and \( \epsilon_{gr} \) respectively.

The above equations were written in an explicit finite difference form (forward-difference formulae) (Simate, 1999) and the resulting system of algebraic equations were solved by using the Gauss-Seidel iterative technique.
Collector Performance

The collector model equations developed by Bala and Woods (1994) were adopted and the back heat transfer coefficient $U_b$, was added in the absorber plate energy balance. For an element $dy$ at a distance $y$ from collector inlet, the equations are given as follows:

Glass cover:

$$h_{af}(T_e - T) + h_{eq}(T_e - T_{wm}) + h_{rc}(T_e - T_s) - h_p(T_p - T_e) = \alpha_{cS}(1 + \varepsilon_{cS}\rho_{PS})\phi$$  \hspace{1cm} (14)

Absorber plate:

$$h_{af}(T_p - T) + h_{rp}(T_p - T_e) + U_b(T_p - T_{wm}) = \frac{\alpha_{pS}\varepsilon_{cS}\phi}{1 - \rho_p\rho_{PS}}$$ \hspace{1cm} (15)

Airflow between absorber plate and glass cover:

$$sGCpa\left(\frac{dT}{dy}\right) = h_{af}((T_p - T) + (T_e - T))$$ \hspace{1cm} (16)

where the temperatures $T$, $T_e$ and $T_p$ are for the local air, cover and absorber plate, respectively.

The radiative and convective heat transfer coefficients are given by Duffie and Beckman (1991) and Bala and Woods (1994). The radiation coefficient from plate to cover $h_{rp}$, is given by:

$$h_{rp} = \frac{\sigma(T_p^2 + T_e^2)(T_p + T_e)}{(1/\varepsilon_{PL}) + (1/\varepsilon_{cL}) - 1}$$ \hspace{1cm} (17)

and the radiation coefficient from cover to the sky $h_{rc}$, is given by:

$$h_{rc} = \varepsilon_{cL}\sigma(T_c^2 + T_s^2)(T_c + T_s)$$ \hspace{1cm} (18)

For the free convection occurring in the collector, the convective heat transfer coefficient between cover and fluid and absorber $h_{af}$, is obtained from Duffie and Beckman (1991) and is given by:

$$Nu = 1 + 1.44[1 - 1708/Ra \cos \gamma](1 - 1708(\sin(1.8\gamma))^{1.6}/Ra \cos \gamma) + [(Ra \cos \gamma/5830)^{1/3} - 1]$$ \hspace{1cm} (19)
where

\[ \text{Nu} = \frac{h_s}{k_a} \]  

(20)

\[ \text{Ra} = \frac{g \beta (T_p - T_c) s^3 \text{Pr}}{v^2} \]  

(21)

The expressions in square brackets are taken as zero when negative. The convective heat transfer coefficient obtained from Eqn. (20) is doubled to give \( h_{af} \).

For forced convection in the collector, the convective heat transfer coefficient between the glass cover and the absorber plate \( h \) is obtained from Duffie and Beckman (1991) and is given by:

\[ h = \left( \frac{k_a}{d_h} \right) 0.0158 \text{ Re}^{0.8} \]  

(22)

where the hydraulic duct diameter \( d_h \) is four times the flow cross-sectional area divided by the wetted perimeter.

The natural and forced convective heat transfer coefficients were compared and the higher value were used in the simulation since the higher value gives a lower thermal resistance and therefore higher heat flux. The left hand side of Eqn. (16) is the heat flux whereas the thermal resistance is a reciprocal of the convective heat transfer coefficient between cover and fluid and absorber \( h_{af} \), appearing on the right hand side of the equation. The higher heat transfer coefficient therefore, shows which of the modes of heat transfer, natural or forced, is dominant.

**Airflow in the Dryer**

The buoyancy-induced pressure head, created above atmospheric pressure in a natural convection solar dryer, initiates airflow through the dryer. As the air flows through the dryer, pressure drops occur in the collector and across the grain bed. The pressure drop across the grain bed is dominant. These pressure drops are equal to the buoyancy induced pressure and are given by (Bala and Woods, 1994):

\[ \Delta P_{th} = \Delta P_{gh} + \Delta P_c + \Delta P_E \]  

(23)

The thermal buoyancy pressure is obtained by adding the various thermal buoyancy pressures generated in different sections of the dryer.
with vertical heights $H_V$ and temperature $T$ and is given by:

$$\Delta P_{tb} = g \beta \rho_a \sum (T - T_{am}) H_V$$  \hspace{1cm} (24)

The pressure drop across the grain bed was calculated from the airflow equation presented by the ASAE Standards (1991) and is given by:

$$\Delta P_{gb} = B \frac{a Q_a^2}{\ln(1 + b Q_a)}$$  \hspace{1cm} (25)

For shelled maize in the range of airflow $Q_a = 0.0056$ to $0.254$ m$^3$/s.m$^2$, the constants are $a = 20700$ and $b = 30.4$. This range covers the airflow in the natural convection solar dryer under study.

The pressure drop across the collector is due to the resistance of the inner surface of the collector to airflow and is given by:

$$\Delta P_c = \frac{G^2 f L}{2 \rho_a d_h}$$  \hspace{1cm} (26)

As the air exits from the collector and from the drying chamber into the atmosphere, a loss in pressure head occurs. This pressure loss is presented here by using the dynamic head loss coefficient $K_{ex}$, at the exit of the collector and dryer.

$$\Delta P_E = K_{ex} \frac{G^2}{2 \rho_a}$$  \hspace{1cm} (27)

**Solution Procedure**

For a given incident solar radiation, collector inlet and ambient temperatures, the mean collector temperature is assumed and then used to determine the mass flow of air through the dryer. This is done by making a comparison between the buoyancy pressure with the frictional and dynamic head losses in the collector, dryer and exit. The mass flow of air is an input to the collector model equations. An iterative procedure is then followed to determine the temperature of collector absorber, air and cover until convergence is achieved when the execution is moved to the deep bed section. The criterion for convergence is that the computed mean collector temperature should not differ from its predecessor by more than 0.0005°C. The converged collector output air temperature and the computed mass flow form the inputs to the deep bed model equations.

The deep bed is divided into a number of thin layers in which the grain properties are assumed constant. This requires that the time interval between
the air into the elemental thin layer and out of it be small enough for the air conditions to be constant. The reduction in moisture content $\Delta M$, the increase in grain temperature $\Delta T_0$, the reduction in air temperature $\Delta T$, and the increase in air humidity $\Delta H$ are computed for the first layer during the time interval $\Delta t$. These calculations are repeated for the rest of the layers until the top of the bed is reached. At the end of each time interval, the mean moisture content of the grain bed is calculated. The whole process in the bed starting with the calculation of the drying constants and equilibrium moisture content, is repeated for each time interval $\Delta t$; each time adjusting the mean moisture content until the sum of the $\Delta t$s equals the pre-set time for the change of ambient boundary conditions.

Next, the collector inlet and ambient temperatures are changed to the new values and the whole process is repeated starting with the assumed mean collector temperature. This procedure is repeated for each new inlet collector and ambient temperature.

The above procedures were programmed in Fortran language.

RESULTS AND DISCUSSION

To verify the model the simulation results were compared to the experimental results by Simate (1999). The experiments were performed on a prototype solar dryer under a solar simulator at the University of Newcastle in the United Kingdom.

Experimental Conditions

The geometric parameters of the dryer (Simate, 1999) defined in Figure 1, and the experimental conditions given here were used in the simulation. Also used in the simulation were radiative properties of the absorber, glass cover and maize grain shown in Table 1. The dryer capacity was 10 kg and the initial grain moisture content was 33.7% dry basis giving a bed depth of 0.04 m. The initial grain temperature was 21.7°C. Table 2 shows the dry and wet bulb temperatures during the experiment. The solar simulator was set at a constant radiation of 635.0 W/m$^2$.

Moisture Content and Distribution

The variation of mean moisture content with drying time is shown in Figure 2. The moisture content was reduced from 33.7% to 16.2% in six hours of drying giving a drying rate of about 0.2 kg/h.
The moisture content distribution across the grain bed at the end of drying is shown in Figure 3. The bottom moisture content is about 2% lower than the mean and the top moisture content is almost the same as the mean and this shows that there are two drying fronts. This distribution is more uniform than that reported in indirect dryers (Bala and Woods, 1994) where the mean was high as compared to the bottom moisture content and the grain at the top was slightly wet due to condensation. Njie and Rumsey (1997) also observed a uniform moisture distribution in the sun drying of maize.

Table 1. Radioactive Properties of Collector and Dryer Glass Cover, Collector Absorber and Maize Grain

<table>
<thead>
<tr>
<th></th>
<th>Collector and dryer glass cover</th>
<th>Collector absorber</th>
<th>Maize grain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short wave</td>
<td>τ 0.811</td>
<td>0.943</td>
<td>0.7753</td>
</tr>
<tr>
<td></td>
<td>α 0.041</td>
<td></td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>ρ 0.151</td>
<td></td>
<td>0.225</td>
</tr>
<tr>
<td>Long wave</td>
<td>τ 0.0</td>
<td></td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>ε 0.892</td>
<td></td>
<td>0.903</td>
</tr>
<tr>
<td></td>
<td>ρ 0.112</td>
<td></td>
<td>0.10</td>
</tr>
</tbody>
</table>

1Duffie and Beckman (1991)  
2Bala and Woods (1994)  
3Arinze et al. (1987)

Table 2. Dry and Wet Bulb Temperatures During the Experiment

<table>
<thead>
<tr>
<th>Elapsed drying time (h)</th>
<th>Dry bulb (°C)</th>
<th>Wet bulb (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>24.3</td>
<td>15.4</td>
</tr>
<tr>
<td>0.5</td>
<td>25.8</td>
<td>15.8</td>
</tr>
<tr>
<td>1.0</td>
<td>26.3</td>
<td>16.2</td>
</tr>
<tr>
<td>1.5</td>
<td>26.8</td>
<td>16.4</td>
</tr>
<tr>
<td>2.0</td>
<td>26.9</td>
<td>16.4</td>
</tr>
<tr>
<td>2.5</td>
<td>27.3</td>
<td>16.4</td>
</tr>
<tr>
<td>3.0</td>
<td>27.3</td>
<td>16.4</td>
</tr>
<tr>
<td>3.5</td>
<td>27.8</td>
<td>17.0</td>
</tr>
<tr>
<td>4.0</td>
<td>27.5</td>
<td>16.8</td>
</tr>
<tr>
<td>4.5</td>
<td>27.5</td>
<td>16.8</td>
</tr>
<tr>
<td>5.0</td>
<td>27.9</td>
<td>17.0</td>
</tr>
<tr>
<td>5.5</td>
<td>27.9</td>
<td>17.2</td>
</tr>
<tr>
<td>6.0</td>
<td>28.3</td>
<td>17.2</td>
</tr>
</tbody>
</table>
SOLAR DRYING OF MAIZE

Figure 2. Mean moisture content changes with drying time in the mixed-mode dryer for 10 kg capacity, 33.7% d.b. initial moisture content and 635.0 W/m² radiation.

Figure 3. Moisture content distribution at the end of drying in the mixed mode dryer for 10 kg capacity, 33.7% initial moisture content and 635.0 W/m² radiation.
cassava chips on wire mesh trays due to direct radiation on top of the cassava bed and an airflow through the bed from below.

**Grain Temperature and Distribution**

The variation of grain temperature at the bottom, middle and top of the bed with drying time is shown in Figure 4. The temperature at the top of the bed does not rise as fast as that at the bottom despite the bed surface receiving direct radiation. This is due to evaporative cooling during the initial stages of drying.

The bed temperature distribution at the end of drying is shown in Figure 5. The heating of the grain bed surface by direct radiation is quite evident from the temperature of grain at the top of the bed that is higher than that in the middle. The temperature at the bottom of the bed is also higher than that in the middle.

![Figure 4.](image)

*Figure 4.* Grain temperatures at the top, middle and bottom of the grain bed in the mixed-mode dryer for 10 kg capacity, 33.7% d.b. initial moisture content and 635.0 W/m² radiation.
Air Temperature at Collector Exit

Figure 6 shows the variation of temperature at collector exit. The temperature from experiment shows an increase in the first two hours and thereafter remains fairly stable. The temperature rise from theory on the other hand, only shows instability in the first one hour and remains stable thereafter. In theory, the heat capacity effect of the collector was not taken into account, the collector is assumed to operate in a steady-state mode and thus the fairly constant temperature. In the experiment, the whole solar dryer was allowed to heat up for one hour to bring the collector to its operating temperature. However, because the dryer was run with no load during the warm up period, the temperature rise in the collector was lower than when the dryer was run with a load due to the higher airflow at no load. This might explain why the temperature rise is low at the start of the drying run. The agreement between theory and experiment is quite good though.

Air Temperature above the Grain Bed and Pressure Drop

The curve for air temperature above the grain bed is shown in Figure 7. The temperature at the start of drying is equal to that of the ambient and then increases continuously to about 60°C. Since this temperature is higher than...
that in the ambient, it increases the thermal buoyancy. The shape of this curve is as expected, giving good agreement between experiment and theory.

The pressure drop across the grain bed is shown in Figure 8. The pressure drop from both theory and experiment continuously increase from start to end of experiment. This could be due to the contribution by the thermal buoyancy created in the space above the grain bed as influenced by temperature of air above the grain bed (Figure 7).

**Figure 6.** Temperature of air at collector exit in the mixed-mode dryer for 10 kg capacity, 33.7% d.b. initial moisture content and 635.0 W/m² radiation.

**Figure 7.** Air temperature above the grain bed in the mixed-mode dryer for 10 kg capacity, 33.7% d.b. initial moisture content and 635.0 W/m² radiation.
The stability of the numerical solution is examined by varying depth and time steps. Tables 3 and 4 show the effect of varying the depth step and time step respectively. These results were generated by using the above experimental conditions. It is evident from Tables 3 and 4 that increasing the depth and time steps twice does not result in big calculation errors due to the stability of the solution.

The $R^2$ value is in the range of 0.996 to 0.999 which shows that the model very closely matches the experimental data.

**CONCLUSIONS**

A new model of simultaneous upward convection and downward conduction has been developed to describe mixed-mode drying. The model has been verified against Simate's (1999) laboratory data and gives a good description of mixed-mode solar drying.

The mixed-mode has two drying fronts, one from the top of the bed moving downwards and the other from the bottom of the bed moving upwards making the mixed-mode have a more uniform bed temperature and moisture content distribution than the indirect mode. There is no serious overdrying and the grain therefore, does not require mixing.
The pressure difference created by a buoyancy force in a duct of a given vertical height and at a temperature higher than ambient is the thermal buoyancy pressure. The main contribution to the thermal buoyancy pressure is the temperature of air in the collector and in the space above the grain bed. This is because, as the temperature of air inside the dryer increases, the air becomes less dense than that in the ambient and therefore rises and creates a flow. Consequently the thermal buoyancy pressure increases gradually throughout the drying period as the grain gets drier and the temperature of air in the space above the grain bed increases due to reduced evaporative cooling. The pressure drop takes place primarily across the grain bed and any trends observed in the buoyancy pressure are similar to those across the bed.

### Table 3. Effect of Increasing Depth Step on the Simulated Mean Moisture Content, the Time Step was Constant at 0.25 s

<table>
<thead>
<tr>
<th>Elapsed drying time (h)</th>
<th>Depth step (m)</th>
<th>Mean moisture content (% dry basis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.0005</td>
<td>24.2</td>
</tr>
<tr>
<td></td>
<td>0.001</td>
<td>24.5</td>
</tr>
<tr>
<td>4</td>
<td>0.0005</td>
<td>19.1</td>
</tr>
<tr>
<td></td>
<td>0.001</td>
<td>19.4</td>
</tr>
<tr>
<td>6</td>
<td>0.0005</td>
<td>16.2</td>
</tr>
<tr>
<td></td>
<td>0.001</td>
<td>16.4</td>
</tr>
</tbody>
</table>

### Table 4. Effect of Increasing Time Step on the Simulated Mean Moisture Content, the Depth Step was Constant at 0.0005 m

<table>
<thead>
<tr>
<th>Elapsed drying time (h)</th>
<th>Time step (s)</th>
<th>Mean moisture content (% dry basis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.25</td>
<td>24.2</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>24.0</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>23.6</td>
</tr>
<tr>
<td>4</td>
<td>0.25</td>
<td>19.1</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>18.9</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>18.6</td>
</tr>
<tr>
<td>6</td>
<td>0.25</td>
<td>16.2</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>16.0</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>15.8</td>
</tr>
</tbody>
</table>
**NOMENCLATURE**

- \(a, b\) constants in airflow equation
- \(a_V\) surface area per unit volume, \(m^2/m^3\)
- \(B\) depth of grain bed, \(m\)
- \(C\) constant in Page equation
- \(C_p\) specific heat, \(J/kg K\)
- \(d\) diameter, \(m\)
- \(d_h\) hydraulic duct diameter, \(m\)
- \(E\) length of drying chamber, \(m\)
- \(f\) friction factor
- \(g\) acceleration due to gravity, \(m/s^2\)
- \(G\) air mass velocity, \(kg/m^2 s\)
- \(H\) absolute humidity, \(kg/kg\) dry air
- \(h\) convective heat transfer coefficient, \(W/m^2 K\)
- \(h_{sf}\) \(h\) from cover and absorber to airflow, \(W/m^2 K\)
- \(h_{Ca}\) \(h\) from cover to atmosphere, \(W/m^2 K\)
- \(h_{fg}\) heat of vaporisation of water in the maize grain, \(J/kg\)
- \(h_{rc}\) radiative heat transfer coefficient, from cover to sky, \(W/m^2 K\)
- \(h_{rg}\) radiative heat transfer coefficient, from maize grain to dryer cover, \(W/m^2 K\)
- \(h_{rp}\) radiative heat transfer coefficient, from absorber plate to cover, \(W/m^2 K\)
- \(h_S\) surface heat transfer coefficient, \(W/m^2 K\)
- \(H_v\) vertical height in buoyancy equation, \(m\)
- \(J\) height of drying chamber above grain bed, \(m\)
- \(k\) thermal conductivity, \(W/m K\)
- \(K\) drying constant in Page equation, \(1/s\)
- \(K_{ex}\) dynamic head loss coefficient
- \(L\) collector length, \(m\)
- \(M\) moisture content, decimal dry basis
- \(M_e\) equilibrium moisture content, decimal dry basis
- \(\Delta P_c\) pressure drop across collector, \(Pa\)
- \(\Delta P_G\) pressure drop at collector and dryer exit, \(Pa\)
- \(\Delta P_{gb}\) pressure drop across grain bed, \(Pa\)
- \(\Delta P_{ob}\) thermal buoyancy pressure, \(Pa\)
- \(Q_a\) airflow per unit area, \(m^3/m^2 s\)
- \(RH\) relative humidity, decimal
- \(s\) spacing between collector cover and absorber, \(m\)
- \(t\) time, \(s\)
- \(T\) air temperature, \(^\circ C\) or \(K\)
$T_c$ collector cover temperature, °C or K
$T_{cD}$ dryer cover temperature, °C or K
$T_p$ collector absorber plate temperature, °C or K
$T_s$ sky temperature, °C or K
$U_b$ back heat loss coefficient, W/m² K
$V$ air velocity, m/s
$W$ collector and drying chamber width, m
$X$ grain depth position, m
$y$ collector length position, m

**Subscripts**
- $a$ dry air
- $am$ ambient
- $c$ cover
- $g$ grain
- $l$ liquid water
- $L$ long wave
- $0$ initial
- $p$ absorber plate
- $S$ short wave
- $t$ time
- $v$ water vapour

**Greek letters**
- $\alpha$ absorptance
- $\beta$ coefficient for cubical expansion, K⁻¹
- $\phi$ radiant flux density normal to collector, W/m²
- $\gamma$ collector angle with horizontal, degrees
- $\epsilon$ emittance
- $\mu$ dynamic viscosity, kg/m s
- $\nu$ kinematic viscosity, m²/s
- $\theta$ grain temperature, °C or K
- $\rho$ density, kg/m³
- $\rho'$ reflectance
- $\sigma$ Stefan-Boltzman constant, W/m² K⁴
- $\tau$ transmittance

**Dimensionless groups**
- Nu Nusselt number
- Pr Prandtl number
- Ra Rayleigh number
- Re Reynolds number
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