MODELING RICE FIELD MOISTURE CONTENT DURING THE HARVEST SEASON – PART II. MODEL IMPLEMENTATION AND VALIDATION

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ABSTRACT. An algorithm was developed to implement the model of Lu and Siebenmorgen (1993) for predicting rice moisture content (m.c.) throughout a harvest season. Equations are presented for generating diurnal patterns of air temperature, relative humidity, and solar radiation from daily maximum and minimum temperatures and relative humidities, and the daily total solar radiation. Rice m.c. was simulated using both hourly and daily field meteorological data for the harvest seasons of 1988 through 1990 at two locations in Arkansas. The m.c.s predicted from both hourly and daily input weather data were closely matched throughout the entire harvest seasons, with the differences being usually less than one percentage point (the average absolute relative differences for the three harvest seasons ranging from 3 to 5%). The model, using both hourly and daily field meteorological data, predicted the rice m.c.s with reasonable accuracy; the average absolute prediction error between measured and predicted m.c. varying between 1.2 and 2.2 percentage points for the three harvest seasons. Large prediction errors (up to six percentage points) were obtained for some of the early harvest dates or when rice was harvested shortly after rain. Dew was predicted to appear on the kernel surface when the air relative humidity was about 94% or higher and could cause up to a four percentage point increase in rice m.c. overnight. Keywords. Rice, Moisture, Harvest, Drying.

Rice moisture content (m.c.) at harvest is an important parameter that is directly related to field yield and milling quality. The ability to predict rice m.c. during the harvest season would facilitate the estimation of proper harvesting schedules that would maximize economic return.

A mathematical model was developed by Lu and Siebenmorgen (1993) to predict rice m.c. throughout a harvest season. The drying/rewatering of rice in the field was considered as a process of simultaneous heat and moisture transfer. The model is capable of predicting the influence of rain and dew on rice m.c. in the field. This article discusses the implementation and validation of the model for predicting rice field m.c. during the harvest season. The specific objectives were to:

- Develop an algorithm to implement the model of Lu and Siebenmorgen (1993) to predict rice field m.c.
- Present mathematical equations for generating the diurnal patterns of air temperature, relative humidity, and solar radiation.
- Validate the model using both hourly and daily meteorological data and rice m.c. data collected at Stuttgart and Keiser, Arkansas, during the harvest seasons from 1987 through 1990.

MODEL IMPLEMENTATION

PROGRAMMING

A program was written in QBASIC to implement the model for predicting rice m.c. throughout a harvest season. A fourth-order Runge-Kutta method was used to obtain the approximate solutions to the systems of coupled differential equations. The program flowchart is shown in figure 1. There are two subroutines in the program: DRYMOD calculates rice m.c. and temperature for the period when dew or rain is not present; and RAINMOD predicts rice m.c. and temperature during a dew or raining period. The input weather data included air temperature, relative humidity, solar radiation, wind velocity, and rain amount, and duration. Two different time steps were used in the simulation program; the time step for rain or dew periods was half of that for the period when dew or rain was not present.

FIELD METEOROLOGICAL DATA

Meteorological data were obtained from the University of Arkansas Rice Research and Extension Center at Stuttgart, Arkansas, for 1988 and 1989 and the Northeast Research and Extension Center at Keiser, Arkansas, for 1989 and 1990. The data included hourly air temperature, relative humidity, total solar radiation, wind velocity, rain amount and duration. The air temperature and relative humidity were recorded using an electronic datalogger (model 21X, Campbell Scientific, Logan, Utah) with a temperature and relative humidity probe (Mode 207, Campbell Scientific, Logan, Utah) contained within a ventilated/shielded enclosure mounted at 1 m height above the ground. The wind velocity at a typical rice panicle height was calculated using the equations given in Appendix 1.

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Figure 1—Program flowchart for predicting rice m.c. throughout a harvest season. (Nomenclature is given in the list of symbols.)

Figure 2 shows the air temperature and relative humidity for a portion of the 1988 harvest season at Stuttgart. The daily relative humidity during the 1988 harvest season was normally between 40 and 90%. The 1989 weather data (not presented) showed that the harvest season was drier than in 1988, with the daily maximum relative humidity usually being lower than 85%. Air temperatures and relative humidities for selected days of the 1990 harvest season at Keiser, Arkansas, are shown in figure 3. The daily maximum relative humidity often reached above 90%, but rarely exceeded 96%.

Figure 3—Hourly air temperature ($T_a$) and relative humidity (RH) for a portion of the 1990 harvest season at Keiser, Ark.

It is more desirable to use daily maximum and minimum air temperature and total solar radiation weather data as inputs for predicting rice m.c., since hourly weather data may not be readily available for most locations. Some weather simulation programs such as WGEN (Richardson, 1985) can also generate this daily weather information. Hence, it was necessary to use/develop equations for generating the diurnal patterns of air temperature, relative humidity, and solar radiation.

Reconstructing diurnal air temperature curves from daily maxima and minima has been attempted in a variety of ways. Reicosky et al. (1989) reviewed some of these models and compared five different methods of calculating instantaneous air temperature from daily maxima and minima. They found the model developed by De Wit et al. (1978) to be the most accurate among the five methods evaluated. However, this model was found unsatisfactory when used to fit the hourly weather data of this study. Therefore, a new method was proposed to model diurnal temperature fluctuations. This method assumes $T_{\text{max}}$ at 1400 h ($t = 14$ h) and $T_{\text{min}}$ at sunrise, and requires the inputs of $T_{\text{max}}$ of the previous day and $T_{\text{min}}$ of the next day for calculating the air temperature of the current day. The day is divided into two segments, from sunrise to 1400 h and from 1400 h to sunrise of the next day. The intervening temperatures are calculated using the following equations:

$$T_a(t) = \begin{cases} T_{\text{max},N-1} + T_{\text{amp},N-1} \cos \left( \frac{\pi}{2} \left( 1 + \frac{t + 10}{t_{\text{rise}} + 10} \right) \right) & 0 \leq t \leq t_{\text{rise}} \\ T_{\text{min},N} + T_{\text{amp},N} \cos \left( \frac{\pi}{2} \left( 3 + \frac{t - t_{\text{rise}}}{14 - t_{\text{rise}}} \right) \right) & t_{\text{rise}} \leq t \leq 14 \\ T_{\text{max},N} + T_{\text{amp},N+1} \cos \left( \frac{\pi}{2} \left( 1 + \frac{t - 14}{t_{\text{rise}} + 10} \right) \right) & 14 \leq t \leq 24 \end{cases}$$

where
\[
\begin{align*}
T_{\text{amp},N-1} &= T_{\text{max},N-1} - T_{\text{min},N} \\
T_{\text{amp},N} &= T_{\text{max},N} - T_{\text{min},N} \\
T_{\text{amp},N+1} &= T_{\text{max},N+1} - T_{\text{min},N+1}
\end{align*}
\]  \hspace{1cm} (2)

t = \text{time of day from midnight (h)}

t_{\text{rise}} = \text{time of day at sunrise, h past midnight}

T_a = \text{air temperature (°C)}

T_{\text{max}} = \text{daily maximum temperature (°C)}

T_{\text{min}} = \text{daily minimum temperature (°C)}

N = \text{current day of the year}

The accuracy of this proposed model will be compared to measured data in a later section. The diurnal relative humidity pattern can be generated, as suggested by Kimball and Bellamy (1986), by assuming that the vapor pressure is constant throughout a day. However, the weather data collected for the three harvest seasons generally showed large variations in the vapor pressure within given harvest days. This means that large differences between observed and predicted relative humidities could be obtained if the vapor pressure was assumed to be constant for each harvest day. Hence, an approach similar to the one for generating air temperature was used to generate the diurnal pattern of relative humidity:

\[
\begin{align*}
\text{RH}(t) &= \begin{cases} \\
\text{RH}_{\text{min},N-1} - \text{RH}_{\text{amp},N-1} \cos \left[ \frac{\pi}{2} \left( 1 + \frac{t+10}{t_{\text{rise}}+10} \right) \right] & 0 \leq t \leq t_{\text{rise}} \\
\text{RH}_{\text{max},N} - \text{RH}_{\text{amp},N} \cos \left[ \frac{\pi}{2} \left( 3 + \frac{t_{\text{rise}}}{14-t_{\text{rise}}} \right) \right] & t_{\text{rise}} \leq t \leq 14 \\
\text{RH}_{\text{min},N} - \text{RH}_{\text{amp},N+1} \cos \left[ \frac{\pi}{2} \left( 1 + \frac{14-t_{\text{rise}}}{t_{\text{rise}}+10} \right) \right] & 14 \leq t \leq 24
\end{cases}
\end{align*}
\]

where

\[
\begin{align*}
\text{RH}_{\text{amp},N-1} &= \text{RH}_{\text{max},N} - \text{RH}_{\text{min},N-1} \\
\text{RH}_{\text{amp},N} &= \text{RH}_{\text{max},N} - \text{RH}_{\text{min},N} \\
\text{RH}_{\text{amp},N+1} &= \text{RH}_{\text{max},N+1} - \text{RH}_{\text{min},N}
\end{align*}
\]  \hspace{1cm} (4)

\text{RH} = \text{air relative humidity}

\text{RH}_{\text{max}} = \text{daily maximum relative humidity}

\text{RH}_{\text{min}} = \text{daily minimum relative humidity}

The diurnal pattern of instantaneous solar radiation was generated using a simple cosine equation proposed by Hirschmann (1974):

\[
S = \left( \frac{\pi}{2D} S_d \right) \left( \frac{10^6}{3600} \right) \cos \left[ \frac{\pi (t-12)}{D} \right]
\]  \hspace{1cm} (5)

where

S = \text{instantaneous solar radiation (W/m}^2\text{)}

S_d = \text{daily total solar radiation (MJ/m}^2\text{)}

D = 0.946 D_a, \text{ day length (rad)}

Figure 4—Comparison of observed (symbols) and model-computed (line) air temperatures for selected days of the 1989 harvest season at Keiser, Ark.

\[
D_a = \text{astronomical day length (rad)}
\]

\[
D_a = \left( \frac{180}{\pi} \right) \left( \frac{2}{15} \right) \cos^{-1} \left[ -\tan \left( \phi \right) \tan \left( \delta \right) \right]
\]  \hspace{1cm} (6)

in which \( \phi \) is the latitude in degrees and \( \delta \) is the solar declination in degrees.

Comparisons of observed and model-computed patterns of air temperature, relative humidity, and solar radiation for four selected days of the 1989 harvest season at Keiser are shown in figures 4 through 6. The computed values using equations 1, 3, and 5 compared well with the observed values of temperature, relative humidity, and solar radiation. The relative humidity model was least accurate of the three models and underestimated the observed values. Overall, equations 1, 3, and 5 predicted air temperature, relative humidity, and solar radiation with reasonable accuracy for clear days, but was less accurate for cloudy or rainy days. Average differences between observed and computed air temperatures ranged from -0.03 to 0.39° C and the average absolute differences from

Figure 5—Comparison of observed (symbols) and model-computed (line) relative humidities for selected days of the 1989 harvest season at Keiser, Ark.
1.39 to 1.64°C for the three harvest seasons from 1988 through 1990. The average differences between observed and computed relative humidities were between 1.8 to 5.6 percentage points for the three harvest seasons with the average absolute differences being 3.3 to 7.6 percentage points. The average differences between observed and computed solar radiation levels were between −0.23 to 7.47 W/m² and the absolute differences between 30.6 and 46.82 W/m².

**SIMULATION RUNS**

Rice m.c. was simulated using both hourly and daily weather data from the three harvest seasons of 1988 through 1990 for Stuttgart and Keiser. In the simulation runs using daily input weather data, equations 1, 3, and 5 were used to generate instantaneous air temperature, relative humidity, and solar radiation data. Daily average wind velocities were used in the model simulations, since wind velocity is not a primary factor affecting rice m.c. change when rain or dew is not present and the data on hourly wind velocity may not be readily available. In the simulation runs using hourly input weather data, the instantaneous temperature and relative humidity values were obtained using linear interpolation. Instantaneous solar radiation and wind velocity values were assumed to be constant over a given hour. Based on the preliminary simulation results, the time step for the periods without dew or rain was chosen to be 0.005 h.

Model validation was performed using the m.c. data for two long-grain varieties, ‘Newbonnet’ and ‘Tebonnet’, from two studies conducted at the University of Arkansas Rice Research and Extension Center at Stuttgart, and at the Northeast Research and Extension Center at Keiser, Arkansas. The experiments were randomized complete block designs and the treatments were time of harvest. There were three replications for the experiments conducted in 1988 and 15 replications for the experiment conducted in 1989 in Stuttgart. Four replications were made for each experiment conducted in Keiser in 1989 and 1990. Rice was hand-harvested around 1:00 P.M. on the specified harvest dates. For the experiments conducted in Stuttgart, rice m.c.s, one sample from each replication, were determined using a standard oven-drying method. For the experiments conducted in Keiser, m.c.s of 8,000 kernels, 2,000 kernels from each replication, were measured using a Shizouka Seiki, CTR-800A individual kernel moisture meter. However, only average m.c.s over the measured kernels were used in the model validation. The individual kernel m.c. data was used for a study (Siebenmorgen et al., 1992) relating head rice yield to individual kernel m.c.s. Detailed information on the experimental procedure for measuring rice m.c. can be found in Siebenmorgen et al. (1992).

All values or equations for the parameters used to execute the simulation program were obtained from other reported studies (see Appendix 2) except for the parameter $k_p$, which accounts for the water flow from the plant to the individual kernels. The flow of water from the plant to the kernels is a complex physiological process. Since no method was found to quantify it, an empirical approach was used to determine the $k_p$ value based on the simulation results. Simulation runs were performed using the hourly meteorological data for Stuttgart in 1989 to determine the parameter $k_p$. The following form was found to be an appropriate functional form of $k_p$ based on a trial-and-error method and comparison of the experimental data and the model predictions of rice m.c.:

$$k_p = 1 - 0.9 \exp \left( -10.8 \times M \right)$$ (7)

where $M$ is the rice m.c. on a decimal dry basis.

As discussed in Lu and Siebenmorgen (1993), the flow of water from the plant to the kernels is expected to cease at a certain m.c. level, $M_c$, during senescence. In this study, the value of $M_c$ was chosen to be 19% (d.b.), based on both simulation results and the studies of Lu et al. (1992) and Siebenmorgen et al. (1992). These studies showed that for long-grain rice varieties grown in Arkansas, the potential field yield and milling yields approach maximum when rice m.c. is about 22%, and that significant reductions in head rice yield occur after rice m.c. decreases to 18%. This indicates that rice senescence takes place approximately between 22 and 18% m.c. Hence, the flow of water from the plant to the kernels is expected to cease below 22% m.c., but above 18% m.c.

**RESULTS AND DISCUSSION**

Figure 7 shows the comparison of observed m.c.s and the model predictions of m.c. for ‘Newbonnet’ long-grain rice grown in Stuttgart in 1989, using both hourly and daily meteorological data. The data points shown are the average of 15 measurements. It was expected that predicted m.c.s would compare well with the experimental data when the rice m.c. was above 19% since the parameter $k_p$ was chosen based on experimental data. However, the model still predicted the experimental data well after the rice m.c. decreased below 19%. The model predictions of m.c. using both hourly and daily meteorological data were closely matched throughout the entire harvest season with the differences being normally less than 1% m.c. (the average absolute relative difference being 3.1%). The average absolute prediction errors over the entire harvest season were 1.2 and 1.5 percentage points for using the hourly and daily meteorological data, respectively. Relatively large
Prediction errors (up to 3.9 percentage points) were obtained for the two harvest dates in which rice was harvested shortly after rain.

Figure 8 presents the simulated daily kernel temperature and actual air temperature for selected days of the 1988 harvest season at Stuttgart based on the hourly weather data inputs. The kernel temperature closely followed the air temperature and was higher than the air temperature during the day and lower than the air temperature at night, with the differences usually being less than 1.5°C. Similar trends in daily kernel temperature change were obtained for the other harvest seasons.

The model predictions of m.c. for 'Newbonnet' rice during the 1988 harvest season at Stuttgart compared well with the experimental data, particularly after rice m.c. decreased to about 20% (fig. 9). Each data point is the average of three m.c. measurements. The predictions of rice m.c. using both hourly and daily weather data were very close except for the short period after the predicted m.c. from the daily weather data inputs decreased to 19%. During that short time period, the differences in predicted m.c. by the two methods were as high as about four percentage points. The average absolute prediction errors over the entire harvest season were 1.7 and 1.3 percentage points using the hourly and daily weather data, respectively. Larger prediction errors (up to 2.8 percentage points) were obtained when rice was harvested above 22% m.c. The occurrence of rain events caused rapid increases in rice m.c., as predicted by the model. However, the rice then lost the absorbed moisture rapidly after the rain ceased. In the early harvest season, the rice m.c. decreased steadily and this decreasing trend was only disrupted by rain events. Dew incidence on the kernel surface was predicted by the model for one day only, with the duration being less than an hour.

Figure 10 shows the comparison of predicted and observed m.c. of 'Newbonnet' rice for the 1989 harvest season at Keiser. Each data point in the figure represents the average of four m.c. measurements. Again, the model predictions of m.c. using both the hourly and daily weather data were closely matched throughout the harvest season.
except for the short period after the predicted m.c. from the daily weather data reached 19%. The model predicted the m.c.s reasonably well throughout the entire harvest season, with respective average absolute errors of 1.5 and 1.6 percentage points when using hourly and daily weather data. A larger prediction error (4.0 percentage points) was obtained for the last harvest date in which rice was harvested a few hours after rain.

In 1990, about one-fourth of the harvest season days were characterized by rain (fig. 11). These rain events caused dramatic changes in rice m.c. The model predictions of rice m.c. did not compare well with the experimental data for some of the early harvest dates; the maximum prediction errors were about 5.4 and 5.9 percentage points when using the hourly and daily weather data, respectively. During this period, the measured m.c. decreased by only about four percentage points for the first 14 days, which was atypical of other field data. Further discussion of the relatively poor performance of the model at high m.c. levels is given later. After the rice m.c. decreased to about 20%, the rice kernel experienced the daily cyclic changes of diurnal drying and nocturnal rewetting if rain events were not present. The model predictions of rice m.c. compared well with the experimental data except for the last two harvest dates, which is speculated to be due to the fact that the air temperature for that time period decreased to near 0°C, which is beyond the normal temperature range that the model applies. It should be mentioned that the 1990 harvest season was extended much longer than the normal harvest seasons in Arkansas.

Dew on the kernel surface was predicted from the hourly weather data inputs for about one-third of the days out of the 58-day harvest season in 1990 at Keiser (fig. 11). The modeling results showed that dew normally appeared on the kernel surface when relative humidity was about 94% or higher. The kernel m.c. could be increased by four percentage points when dew lasted 9 h. Lagué and Jenkins (1991) reported a five percentage point increase in m.c. overnight for rice grown in Davis, California, where dew often persists for more than 12 h. No dew was predicted by

the model for the 1989 harvest season at Stuttgart and Keiser.

Overall, the model adequately predicted rice m.c. during the three harvest seasons. Large prediction errors were sometimes obtained when rice was harvested at high m.c.s (> 25%). A possible reason for this is the fact that nonuniformity in kernel m.c. in the field was more pronounced at higher m.c.s (Kocher et al., 1990), which could have produced greater m.c. measurement errors. As the average m.c. decreased, the individual kernel m.c.s became less variable on a panicle and among panicles for different field plots. Hence, the model would be expected to give a better prediction for the later harvest season than for the early harvest season. The relatively poor performance in some of the early harvest seasons may have also been due to the empirical equation used for estimating the interaction of the plant with the panicle or individual kernels. The flow of water from the plant to the panicle is influenced by both environmental conditions and the physiological activities of the plant. The modeling results showed that a substantial amount of water lost by the kernels was compensated by the plant during the early harvest season. This indicates that determination of the interaction between the plant and kernels is crucial for accurate prediction of rice m.c. during the early harvest season. The parameter k_p determined in this study appeared to be suitable for long-grain rice grown in Arkansas. However, it is not clear whether the parameter k_p is applicable to other, different varieties under various geographic locations.

Predicted m.c.s from the daily weather data were consistently lower than those from the hourly weather data, although the differences were usually less than one percentage point. This is likely due to the fact that the generated relative humidities were lower than observed values.

**SUMMARY AND CONCLUSIONS**

An algorithm was developed to implement the model of Lu and Siebenmorgen (1993) for predicting rice m.c. during the harvest season. Mathematical equations were presented for generating the diurnal patterns of air temperature, relative humidity, and solar radiation from the daily maximum and minimum temperature and relative humidity, and the daily total solar radiation. The computed values of temperature, relative humidity, and solar radiation compared reasonably well with the observed values for clear days and were less accurate for overcast or rainy days.

Rice m.c. was simulated using both the hourly and daily meteorological data for the harvest seasons from 1988 to 1990 at Stuttgart and Keiser, Arkansas. Predicted m.c.s from the two weather data sets were closely matched with differences being normally less than one percentage point. The model-predicted m.c.s compared reasonably well with the observed m.c. data with average absolute prediction errors of less than 2.2 percentage points for the three harvest seasons. Large prediction errors (up to six percentage points) were obtained for some of the early harvest dates or when rice was harvested shortly after rain. The model-predicted kernel temperature closely followed the air temperature and the differences were usually less than 1.5°C.
The simulation results showed that the occurrence of rain events caused dramatic increases in rice m.c., but that the rice then lost the absorbed moisture rapidly after the rain ceased. Dew on the kernel surface was predicted for the 1988 and 1990 harvest seasons when the relative humidity was approximately 94% or higher and caused up to 4 percentage points increase in rice m.c. overnight. The results also showed that during the early harvest season a substantial amount of water lost by the kernels was compensated by the plant.

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REFERENCES


LIST OF SYMBOLS

\[a\] ratio of kernel surface area to volume \(\text{m}^{-1}\)

\[c_g\] kernel specific heat \(\text{J/kg.} \cdot ^\circ \text{C}\)

\[d\] diameter of the equivalent sphere of a rice kernel \(\text{m}\)

\[D\] day length \(\text{rad.}\)

\[D_a\] astronomical day length \(\text{rad.}\)

\[h\] heat transfer coefficient \(\text{W/m}^2 \cdot ^\circ \text{C}\)

\[h_d\] moisture transfer coefficient \(\text{m/s}\)

\[k\] drying/rewetting parameter

\[k_c\] rewetting parameter for rice soaking

\[k_p\] parameter accounting for the water flow from the plant to kernels

\[L_w\] latent heat of vaporization/condensation of water \(\text{J/kg} \cdot \text{H}_2\text{O}\)

\[L_{wg}\] latent heat of vaporization of water in rice \(\text{J/kg} \cdot \text{H}_2\text{O}\)

\[M\] average kernel moisture content \(\text{kg} \cdot \text{H}_2\text{O/}\text{kg dry mass}\)

\[M_e\] equilibrium moisture content \(\text{kg} \cdot \text{H}_2\text{O/}\text{kg dry mass}\)

\[M_o\] kernel initial moisture content \(\text{kg} \cdot \text{H}_2\text{O/}\text{kg dry mass}\)

\[M_w\] amount of dew on the kernel surface, expressed as equivalent kernel moisture content \(\text{kg} \cdot \text{H}_2\text{O/}\text{kg dry mass}\)

\[n\] drying/rewetting parameter

\[N\] current day of the year \(\text{day}\)

\[N_H\] relative humidity

\[R_{H_{\max}}\] daily maximum relative humidity

\[R_{H_{\min}}\] daily minimum relative humidity

\[S\] instantaneous solar radiation \(\text{W/m}^2\)

\[S_d\] daily total solar radiation \(\text{MJ/m}^2\)

\[t\] time of the day from midnight \(\text{h}\)

\[t_{rise}\] time of day at sunrise from midnight \(\text{h}\)

\[T_{a}\] air temperature \(\circ ^\text{C}\)

\[T_{g}\] kernel temperature \(\circ ^\text{C}\)

\[T_{max}\] daily maximum temperature \(\circ ^\text{C}\)

\[T_{min}\] daily minimum temperature \(\circ ^\text{C}\)
\( U_c \) wind velocity at the height of rice canopy  
\( U_g \) wind velocity at the rice panicle height  
\( U_w \) wind velocity measured at weather station  
\( Z_c \) height of rice canopy from the ground  
\( Z_g \) height of rice panicle from the ground  
\( Z_o \) zero plane displacement  
\( Z_w \) height of weather recorder from the ground  

\( \alpha \) kernel short-wave absorptivity  
\( \beta \) albedo of the kernel surface  
\( \delta \) solar declination  
\( \varepsilon \) kernel long-wave emissivity  
\( \rho_g \) kernel density  
\( \sigma \) Stefan-Boltzmann constant  
\( \phi \) latitude

**APPENDIX 1 – ESTIMATION OF WIND VELOCITY AT RICE PANICLES**

The following equation was used to estimate the wind velocity at the top of rice canopy (Martin, 1971; Pedro and Gillespie, 1982):

\[
U_c = U_w \left( \frac{Z_c - Z_o}{Z_w - Z_o} \right)^q
\]

where \( Z_o \) is the zero plane displacement and was estimated as \( Z_o = 0.64Z_c \) (Monteith, 1973). Values of \( q \) were determined by Pedro and Gillespie (1982) to be 0.3 to 0.5 for soybean, and 0.4 to 0.8 for corn. The value of \( q \) for rice is not available and was estimated to be 0.5 based on the results for corn and soybean.

The actual wind velocity at rice panicles was estimated as (Landsberg and James, 1971):

\[
U_g = U_c \left[ 1 + n_d \left( 1 - \frac{Z_c}{Z_g} \right) \right]^{-2}
\]

Landsberg and James (1971) reported that the mean values of \( n_d \) for corn and beans are about 2.1 and 2.8, respectively. In this study, the \( n_d \) value was chosen to be 2.5.

**APPENDIX 2 – EQUATION PARAMETERS**

This appendix shows the values and equations for the parameters used in the mathematical model.

**KERNEL PHYSICAL CHARACTERISTICS**

<table>
<thead>
<tr>
<th>'Newbonnet'</th>
<th>'Tebonnet'</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a = 2363.4 )</td>
<td>( a = 2363.4 )</td>
</tr>
<tr>
<td>( d = 0.00332 )</td>
<td>( d = 0.00332 )</td>
</tr>
<tr>
<td>( Z_c = 1.09 )</td>
<td>( Z_c = 1.27 )</td>
</tr>
</tbody>
</table>

\( \rho_g = 1436 - 420 \frac{M}{1 + M} \)  
(Wratten et al., 1969)

\( c_g = 1109 + 4477 \frac{M}{1 + M} \)  
(Haswell, 1954)

\( L_{wg} = (1+2.566e^{-20.176M})L_w \)  
(Nguyen, 1985)

where

\[ L_w = 1000 \times (2502.535259-2.38576427T_g) \]  
(ASAE, 1991)

**HEAT AND MASS TRANSFER COEFFICIENTS**

\[
h = \frac{0.0256}{d} \left[ 2 + 137.65 \left( \frac{U_g}{d} \right)^{0.5} \right]
\]

\[
h_d = \frac{0.246 \times 10^{-4}}{d} \left[ 2 + 130.86 \left( \frac{U_g}{d} \right)^{0.5} \right]
\]

(Loncin and Merson, 1979)

**DRYING/REWETTING PARAMETERS**

**No Water on the Kernel Surface.**

\[
k = 0.01579 + 0.0001746T_g - 0.01413RH
\]

\[
n = 0.6545 + 0.002425T_g + 0.07867RH
\]

\[
M_e = 0.29394 - 0.0460151n[-(T_a + 35.703) \ln(RH) ]
\]

(Wang and Singh, 1978; ASAE, 1991)

**Water on the Kernel Surface.**

\[
K_c = 0.01239306 + 0.0020122T_g - 0.004343T_gM_o
\]

(Lu et al., 1994)

**Radiation Parameters.**

\( \alpha = 0.5 \) (Massie and Norris, 1965)

\( \beta = 0.25 \) (Monteith, 1973)

\( \varepsilon = 0.98 \)

\( \sigma = 5.673 \times 10^{-8} \)