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Development of in-store dryer model for corn for varying inlet conditions

Xu Ma, R.H. Driscoll and G. Srzednicki*

UNSW Australia, School of Chemical Engineering, Sydney NSW 2032 Australia; *Correspondence: g.srzednicki@unsw.edu.au

Abstract. Many thin layer drying models have been developed for constant inlet conditions. During deep bed drying, drying air conditions vary with position in the bed and also vary with time, so models developed for thin layers under constant conditions are not valid for deep bed drying analysis. A new thin layer drying rate model (called the two-layer model) is presented which allows for varying air conditions. The model was applied to corn by retro-fitting the model to Page's mode as fitted by Li and Morey (1984). The model was then incorporated into a deep bed simulation, and the results compared with pilot plant drying data. During drying experiments, constant air conditions and varying air conditions were both tested. For constant conditions, all models gave reasonable agreement, but for varying drying conditions, the diffusion model showed an ability to respond better to changes.

Key words: drying, corn, diffusion model, two layer model, varying air conditions.

INTRODUCTION

Food dehydration is a unit operation consisting of removing moisture from a liquid, solid, or semi-solid feed material in order to control its bioactivity. Reduction of moisture reduces the risk of spoilage, so extends the shelf-life of foods. There are various mechanisms of food spoilage, which can be categorised as microbiological or chemical in nature. Microbiological causes of deterioration (such as bacteria, yeasts and moulds) need a wet substrate and a high water activity (a_w). The lower limits of a_w for bacteria and moulds are 0.91 and 0.80 respectively (Smith, 2003). Dehydration reduces water activity, and after dehydration to below the microbial limits, the low a_w environment is not suitable for bacterial and fungal growth. Chemical and biochemical causes of deterioration are also controlled by drying, including enzymic reactions, non-enzymic browning and lipid oxidation, which are not completely stopped but are significantly slowed down by the reduction in available water. Drying also helps preserves quality attributes of foods such as flavour and nutritive value, provided moderate drying temperatures are used. Moreover, dehydrated foods are easy to transport because of reduced weight or volume.

With a total production of 872 Mt in 2012 (Statista, 2015), corn is the highest volume grain crop produced in the world. Although in various parts of the world sun-drying of corn is still practiced, the fact that the drying performance is affected by weather conditions and that this process is often slow, leads to mould growing and results in production of mycotoxins (especially aflatoxins), which may harm human and animal health.

As a result, mechanical drying of corn is being increasingly adopted, especially among major producers of this crop. Various types of dryers are used for corn drying, for example column dryers or fluidised bed dryers for drying of very wet grain at high temperature with a continuous flow of grain or deep bed dryers with a static bed for grain at moisture content below 18% wet basis (wb). Deep bed dryers are often used for corn harvested under the prevailing climatic conditions in Australia, but since deep-bed models are based on thin-layer drying models, development of such a model for corn was the main focus of this study.

Dehydration of foods is a special challenge for food engineers, due to the complexity of food structure, texture and chemical composition. In order to predict dryer behaviour, mathematical models of the drying process have been developed. For accurate prediction of the drying behaviour of a food material these models are based on knowledge of drying principles, psychrometrics, product thermo-physical properties and the principles of heat and mass balance and transfer.

To reduce this complexity, in practise, many experimenters instead develop empirical or semi-empirical models of thin layer drying rates, which are then fitted to experimental data obtained under constant drying conditions. Drying models constructed for thin layers of a specific food product are then often applied to the deep bed dryers, commonly used for corn.

In a deep bed dryer, air passes from the inlet through successive layers of granular material before exiting the bed. Mathematically, each layer can be treated as a thin layer of material. Since each layer interacts with the drying air, air conditions are modified from inlet to outlet, and so each layer interacts with differing air properties.

Over time, successive layers will tend towards moisture equilibrium with the inlet air. Thus not only does each layer interact with different conditions, but those conditions are changing with time as the product dries.

The above discussion assumes the inlet air stays constant, but in commercial practice, this is not valid, as the inlet air is affected by changing ambient conditions or changing control setpoints. As a result, no layer in a deep bed receives the same air conditions over time. Thin layer drying models are normally developed using constant conditions only.

A number of thin layer drying models have been developed, and used for deep bed drying of grain. Among the most successful equations predicting the drying behaviour of corn are Page's (Li & Morey, 1984), a two-compartment (Henderson (1974) and a modified two-compartment model (Verma et al., 1985). However none of these takes into account changing air conditions, and so are not valid for application to deep bed drying.

A new thin layer drying model was developed by the Food Engineering Research Group at UNSW in Sydney, which has a theoretical basis in diffusion and surface transfer theory, but is able to respond to varying inlet conditions. The product is modelled as two separate compartments, only one of which interacts with the drying air, the other being buried within. No specific shape is assumed for the product, but the model can conveniently be represented by concentric spheres.

The aim of this study was to investigate the drying behaviour of a deep bed of corn using a form of diffusion model adapted for varying inlet conditions, and to test its responsiveness to changing conditions.

THEORETICAL DEVELOPMENT

Page's (reference) empirical model is one of the most successful models for predicting drying time and moisture ratio, and has been widely used in food product drying. Li & Morey (1984) applied Page's model to corn drying data. Page's model can be expressed as:

$$MR = \frac{M - M_e}{M_0 - M_e} = \exp(-kt^n) \quad (1)$$

where: MR is called the moisture ratio; M is moisture content, % dry basis (%db); M_o is initial moisture content, %db; M_e is equilibrium moisture content, %db; k, n are drying constants; t is time.

The constant k is normally assumed to exhibit Arrhenius temperature dependence, requiring determination of activation energy, h. The three drying constants k, n and h were obtained by Li and Morey (1984) by fitting the equation to experimental data.

Unlike Page's model, the new model is based on diffusion theory, with the product being composed of two layers (as for example was done by Verma et al., 1985). Fig. 1 represents the structure of the product. Layer 1 is the interior of the product and layer 2 is the layer in contact with the surface, and which interacts with the drying air. Note that the layers do not physically have to be spherical the only geometric requirement is that layer 2 wraps around layer 1 to prevent its contact with the drying air.

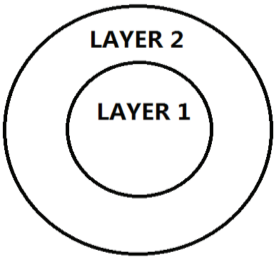

Figure 1. Structure of a product representec by two layers (Verma et al., 1985).

Define a mass ratio constant μ as:

$$\mu = m_{s2} / m_{s1} \quad (2)$$

where: m_{s1}, m_{s2} are the masses for each layer on a dry basis.

The drying rates for each layer (using a first term approximation to the diffusion equation and including surface evaporation) are:

$$\frac{dM_1}{dt} = -k_1\mu(M_1 - M_2) \quad (3)$$

$$\frac{dM_2}{dt} = -k_1(M_2 - M_1) - k_2 A(M_2 - M_e) \quad (4)$$

The model moisture in the product can be calculated by equation (6).

$$M = \frac{M_1 + \mu M_2}{1 + \mu} \quad (5)$$

where: M is the average moisture content; M_1, M_1 are the layer moisture contents; k_1, k_2 are rate constants.

The reason for inserting a factor μ on the right-hand side of equation (4) is to ensure mass balance is observed, which requires the mass leaving layer 1 to be equal to the mass entering layer 2 at the layer interface. The second term in equation (5) expresses the rate of evaporation from the surface. This could be estimated theoretically (for example from the wet bulb equation), but since product properties change during drying, it was thought best to leave this as a model parameter, determined by best-fit to drying data.

Since this model is in written in a differential form, it was implemented on computer using finite difference approximations.

Constants k_1 and k_2 are assumed to be dependent on temperature (Arrhenius):

$$k_1 = k_{10} \times \exp(-h_1/RT_k) \quad (6)$$

$$k_2 = k_{20} \times \exp(-h_2/RT_k) \quad (7)$$

where: h_1, h_2 are heat activation energies (J kmol.K^{-1}); k_{10} and k_{20} are constants; T_k is temperature (Kelvin).

The method could be extended to further layers, but two layers was considered adequate, because integration of the resulting equations (4), (5) and (6) gives a form of equation similar to the standard two compartment model (Henderson, 1974), with two exponential terms and two constants. The integration is difficult, requiring successive elimination of M_1 and M_2 to give a final second order differential equation in M which when solved gives the two-term exponential form.

Equilibrium moisture content data published by Chen & Morey (1989) were used to estimate M_e (see Table 1).

Table 1. Predicted final Me values required for drying runs (using Chen and Morey's equation, 1989)

T (°C)	RH (%)	Me (%db)
71	2	1.82
71	10	4.00
60	4	2.66
60	28	7.19
49	5	3.12
49	40	9.33

MATERIALS AND METHODS

Corn samples

The samples of hybrid waxy corn were supplied by Ingredion ANZ Pty Ltd in Lane Cove NSW 2066 (Australia). The initial moisture content (MC) was 12% wet basis (wb) or 13.6% dry basis (db). They were kept in a cold room at a temperature (T) of 3.5 °C and 55% relative humidity (RH) prior to rewetting pre-treatment.

Conditioning of corn samples

Before conducting the drying experiments, the samples were taken out of the cold room and left in the lab to reach ambient temperature (about 23 °C). In order to prevent mould growth during rewetting, the samples were subjected to surface disinfestation by dipping them in a 1% hypochlorite solution for 1 min.

After harvest, corn has a moisture content between 23–26%wb (30–35% db) and such were the required levels for drying experiments. Thus, the seeds samples were rewetted by adding a calculated amount of distilled water. Then, the seeds were mixed daily and kept at a temperature of 2–5 °C for approximately 7 days to equalise the moisture content distribution and reduce the risk of spoilage. The moisture content of the seed samples was determined by the oven method in accordance with ASAE Standards. For moisture content determination, 15 g of corn seeds were dried at 103 °C for 72 h in a convection oven. The moisture content of seeds was calculated by using the weight loss after drying in the oven. A rapid method (11 min) using the infrared lamp (Mettler LP12) and a balance for ground samples was used for assessment of moisture content of samples during rewetting.

Fitting the Two Layer model

The Page model was assumed to be a good description of the thin layer drying rate of corn for constant aeration conditions. The new Two Layer model was retro-fitted to the Page model, using the method of least squares to minimise the difference between the models. This allowed direct comparison of the capability of the two models to describe changing conditions. The calculated average moisture content M shows good agreement with Page's model. Comparison runs were generated for typical corn drying conditions, and an example is shown below (Fig. 2).

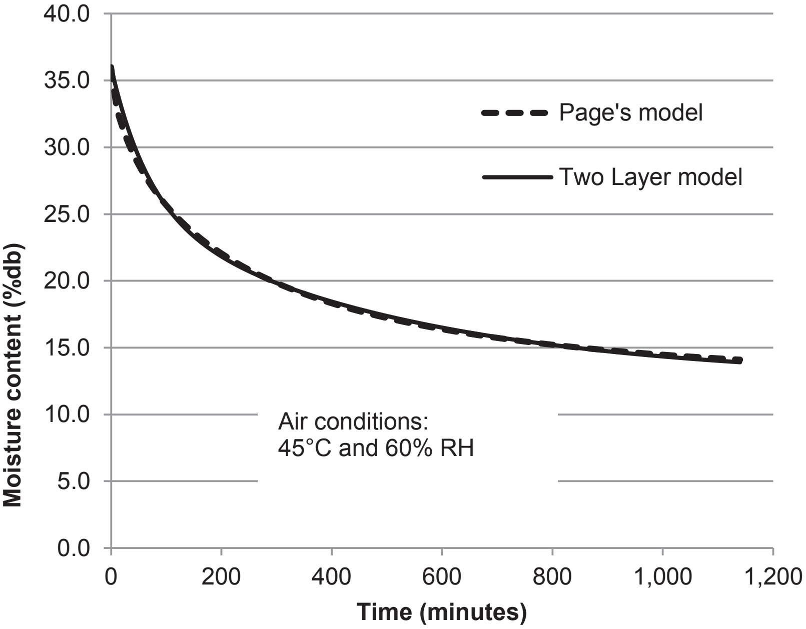

Figure 2. Example demonstrating agreement of retro-fitted Two Layer model to Page's model.

Drying experiments

The in-store dryer built by the Food Engineering Group at the UNSW was used for the deep bed drying experiments (see Fig. 3).

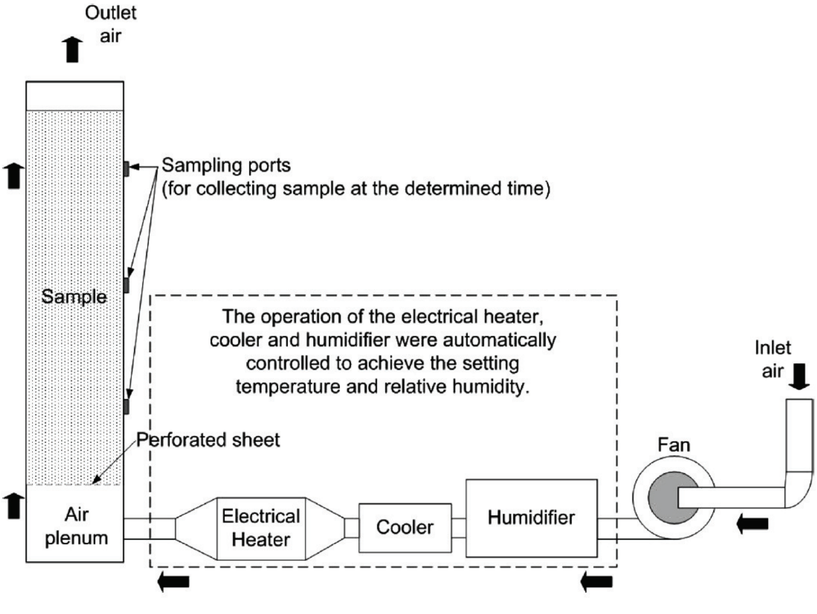

Figure 3. Schematic of the in-store dryer used in the experiments. Source: Jittanit et al. (2010).

The dryer is computer controlled and includes the following hardware:

- SWINNERTON centrifugal fan 7.5 kW with backwards curved blades
- Drying bin 1 tonne of corn capacity
- Heating unit (four heating steps: 7.5 kW, 1.5 kW, 0.75 kW and 0.75 kW)
- Air chilling unit (Carrier 30RQ005, 14.6 kW)
- Chilled water tank for cooler (not shown)
- Steam generator for humidifier (SIMONS model 25/100, 24 kW, not shown)
- Armstrong humidifier model FSA-1
- Landis & Staefa actuator model SKD62
- TOSHIBA variable speed drive model VF-S7 for fan control.
- T-type thermocouples, RH probes and RTD temperature sensors were fitted to the drying bin.

The drying conditions are shown in Table 2. In contrast to the conventional practise of keeping the process parameters constant (T and RH) during the whole run, this study used changing conditions where both temperature and relative humidity were changed during drying runs.

Table 2. Drying conditions for the five drying runs

Run No	Condition 1		Condition 2		Condition 3	
	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)
1	40	40	50	40	30	60
2	40	40	25	40	35	60
3	35	50	30	60	35	50
4	40	50	30	50	40	50
5	40	50	40	50	40	40

In spite of having a PID controller, the conditions could not always be precisely achieved due to the response time of the system controllers and actuators.

RESULTS AND DISCUSSION

In all 5 runs, the corn was dried to a final moisture content of about 12% dry basis. The air speed was determined by hotwire anemometer traverses to be about 0.73 m s^{-1} on average. Due to air vibration caused by the fan and poor relative humidity control, all data were smoothed (running average over 5 points) for presentation. However actual inlet data were used as input for the drying simulation.

Temperature data were chosen as the basis for comparison, as temperatures can be measured without disturbing the bed of corn. Five sensors were located at 20 cm intervals within the experiment bed, and these could be compared with simulated data.

Fig. 4 is an example comparison between the pilot plant (real) data and the simulation, for the first (inlet) layer of the deep bed. The dryer was operated empty for 4 hours, to allow the system to equilibrate, and then loaded over a period of 30 min (as can be seen by the temperature spike at 4 hours). For this run, changes in inlet drying conditions were made after 25 hours and again after 34 hours, as can be seen in the temperature data for layer 1. Also the effect of fluctuations in ambient conditions can be seen in the form of small perturbations in the drying data (dotted line).

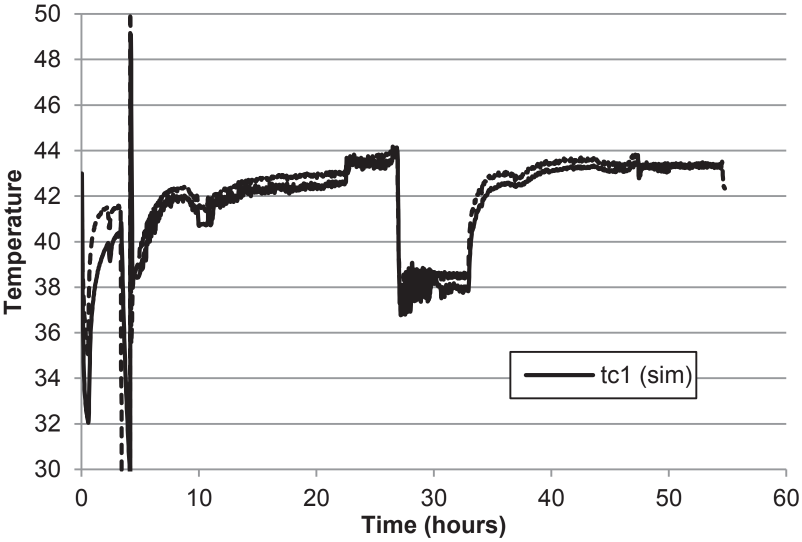

Figure 4. Comparison between data and model for layer 1 (near inlet) of first run.

Fig. 5 compares the data and simulation for the 5th layer (near outlet). Although the agreement is not as good as for Fig. 4, the simulation shows excellent responsiveness under changing conditions. The other four runs gave similar results.

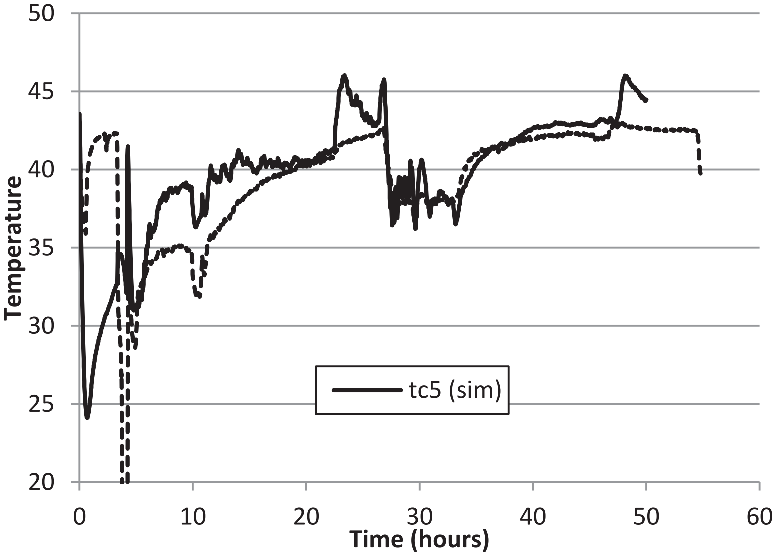

Figure 5. Comparison between data and model for layer 5 (near outlet) of first run.

Figs 6 and 7 show a comparison between the data and a different model, a two compartment model for a deep bed dryer using the Li and Morey (1984) model for thin layer drying. By comparing Figs 4 and 6 directly (for the first or inlet layer), and Figs 5 and 7 directly (for the outlet layer), the differences between the models can be seen. In both cases, the two layer model shows a better agreement between data and model. Similar results were obtained using other models for other experimental runs.

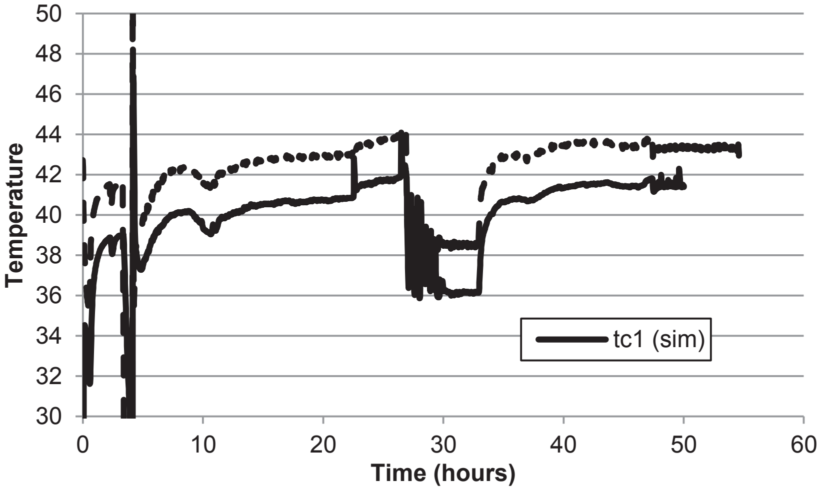

Figure 6. Comparison between data and Two Compartment model for layer 1 (near inlet) of first run.

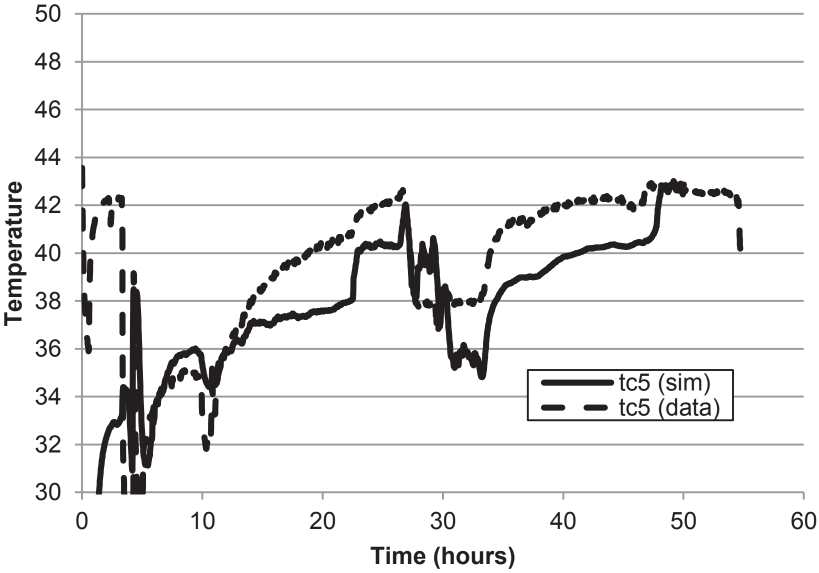

Figure 7. Comparison between data and Two Compartment model for layer 5 (near outlet) of first run.

CONCLUSIONS

A new method for modelling thin layer drying rates has been presented, which uses differential forms of models to allow response to changing air drying conditions, and so giving a model which could be used for deep-bed simulation.

Two factors give an improved likelihood for correct modelling of drying rates through a deep bed, which are the differential form of the model and storage of moisture content information M_1 and M_2 for two layers. Further layers would give little benefit for the same reason that a two compartment model of thin layer drying rates is adequate for most practical situations, and in fact a single compartment model is often enough.

The results show that the model does respond correctly to changing inlet conditions, although agreement between the model and data is not always good. The model also provides a theoretical basis for understanding and predicting tempering effects during conditioning of grain in holding silos.

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REFERENCES

ASAE 1988. ASAE Standards. ASAE S352.2: Moisture Measurement–Ungrounded Grain and Seeds, ASAE: St. Joseph, MI.

Chen, C.C. & Morey, R.V. 1989. Equilibrium relativity humidity (ERH) relationships for yellow-dent corn. *Transactions of the ASAE* **32**(3), 999–1006.

Henderson, S.M. 1974. Progress in developing the thin layer drying equation. *Transactions of the ASAE* **17**, 1167–1172.

Jittanit, W., Srzednicki, G. and Driscoll, R.H. 2010 Corn, Rice and Wheat Seed Drying by Two-Stage Concept, *Drying Technology* **28**(6), 807–815.

Li, H., & Morey, R.V. 1984. Thin layer drying of yellow dent corn. *Transactions of the ASAE* **27**(2), 581–585.

Smith, P.G. 2003. Introduction to Food Process Engineering, Kluwer Academic/Plenum Publishers, New York, p. 320.

Statista 2015. http://www.statista.com/statistics/263977/world-grain-production-by-type. Accessed 31.01.2015.

Verma, L.R., Bucklin, R.A, Ednan, J.B. & Wratten, F.T. 1985. Effects of drying air parameters on rice drying models. *Transaction of the ASAE* **28**, 296–301.