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Review Article

MATHEMATICAL MODELLING OF HEAT AND MASS TRANSFER IN AGRICULTURAL GRAIN DRYING

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Abstract: Mathematical modeling of grain drying is now extensively used in agricultural engineering research. Numerous models have been proposed to describe the heat and mass transfer processes in the elementary types of convective grain drier, namely fixed bed, cross-flow, concurrent-flow and counter-flow. There is extensive prose concerned with the general area of drying in the field of process engineering. It is significant, with an ever-increasing demand for the precise modeling of compound drying systems, for the researcher to recognize the basic assumptions in the various models and hereafter to be aware of the limitations in using them. However, most of this prose accentuates with 'equilibrium' exchange processes and not with the problems of obtaining a detailed description of the product state at all points throughout the drier over the duration of drying. The main influence of this review is the demonstration of some of the partial differential equation (p.d.e.) models which have been used by agricultural engineers incomplete simulations of deep bed drying Several types of mathematical models have been developed to describe the heat and mass transfer processes in grain drying. The present paper primarily emphasizes the description of these processes in deep bed drying.

Keywords: *Drying, Modeling, Heat-mass transfer processes, Driers*

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Introduction

Drying is the removal of moisture *e.g*., reducing water activity from a product, which could slow down the pace of deterioration and maintain the quality. Agricultural crops are mostly dried and conditioned by artificial means. The need for greater yields and storage for a longer duration demands a high degree of control over various properties of the final product. The presence of excess moisture in the stored crop can lead to the growth of moulds and infestation by insects and hence cause damage. Grain is graded according to several physical properties such as moisture content, bulk density, germination and contamination.

The temperature and humidity of the drying air play a dynamic role in the speed and efficiency of drying. Thus, agricultural driers are often characterized according to whether the air temperature is low (up to 5°C above ambient temperature), medium (40-250°C), or high (up to 1000°C). At high temperatures, one can get increased throughput of grain but this can also lead to deterioration in the grain properties e. g. germination. Significant importance should be given to grain temperature and moisture content during the drying process so that safe operating temperatures may be determined for a given type of drier.

Evidently, suitably constructed models can be used to help with the design of new driers and to promote the more efficient use of existing driers.

Heat and Mass Transfer in Agricultural Grain Drying Models

Sherwood (1936) [1] observed that the drying of biological materials in thin layers ventilated by through flow of air has been observed to take place in two or more distinct periods.

In very wet material, there may be an initial constant rate drying period during which the material is fully saturated and has a surface covering of free water. The rate is then only dependent on the external conditions and is given approximately by Brooker *et al* (1974) [2].

$dM/dt= h/h_{fg} (T-T_{wb})$

Where, T_{wb} represents the wet bulb temperature of the drying air.

The work of Luikov (1966) [3] on capillary-porous bodies has formed the basis for a number of recent models involving partial differential equations for the temperature and moisture content distributions within the individual grain kernel.

In particular, Husain *et al* (1973) [4] solved a coupled heat and mass diffusion model as part of a simulation to predict the drying characteristics of rough rice. However, the thermal diffusivity is large compared to the moisture diffusivity in most applications, in general, it is thought to be sufficiently accurate to solve the moisture diffusion equation alone for the moisture distribution within the kernel. This results in an estimation of the moisture loss from the individual kernel.

This single equation model has been used by a number of workers. For example, Ingram (1976) [5] integrated the model in an overall fixed bed simulation. The grain kernel is represented by a variety of geometric shapes, such as a sphere and as lab, he made use of series solutions to the diffusion equation given in the appropriate form. His solution considered the varying surface conditions of the kernel.

Lewis (1921) [6] projected a model analogous to Newton's law of cooling. He recommended that the rate of drying be assumed to be directly proportional to the difference between the moisture content of the material being dried and its equilibrium moisture content (e. m.c.) - the e. m. c. of a material being the moisture content corresponding to vapour pressure equilibrium of the material with its environment. Mathematically it is expressed in the form

$dM/dt= -k (M-M_e)$

where k is known as the drying constant.

As discussed above this model is based on the diffusion theory but assumes that the resistance to diffusion occurs mainly in a thin outer layer of the body. Numerous workers have adapted the basic model to represent thin-layer data more accurately over a wide range of temperature and moisture content. For example, Henderson and Pabis (1961) [7] replaced the constant k by a drying rate coefficient in the form of an Arrhenius type relation involving temperature.

A recent review of models for the falling rate drying of fully exposed biological materials has been given by Sharaf-Eldeen *et al* (1979) [8].

Deep bed models are generally divided into three types, namely logarithmic or exponential, layer by layer or 'heat and mass balance', and partial differential equation models, see Morey *et al* (1978) [9]. The classification is somewhat arbitrary because of the overlapping features in these models.

Hukill (1954) [10] proposed the first model of logarithmic from a simplified analysis of deep bed drying. Assuming that the(time) rate of drying at some given depth x after time t is proportional to the (spatial) rate of decrease in air temperature at (x, t) obtained

$G_aC_a \; \delta T/\delta T = \rho_p \; h_{fg} \; \delta M/\delta t$

This is equivalent to assuming that the (sensible) heat energy lost by the air provides solely the latent heat of vaporization required to dry the grain and neglects sensible heating of the grain. Further, assuming 'fully exposed' grain conditions at the air inlet point, and hence an empirical boundary condition of the form, with a similar form of initial condition for the temperature distribution throughout the bed, Hukill obtained the formula

$MR = 2^X / (2^X+2^T-1)$

where X and T are dimensionless depth and time variables respectively. However, he found that his model underestimated the time required to dry grain to specified moisture content and recommended that this was due to inaccuracies in the thin-layer type grain boundary condition. Barre *et al* (1971) [11] obtained the analogous expression

$MR = e^X / (e^X + e^T -1)$

and hence an expression for the drying time required to reach a given mean moisture content, of the form

$T=\ln \{(e-1) / (e^{MR} -1)\}$

They applied their model to crossflow drying. More recently, Young and Dickens (1975) [12] used Hukill's model to estimate the costs of grain drying in fixed bed and cross-flow systems and Sabbah *et al* (1979) [13] used such a model to replicate solar drying of grain. Because of their simplicity logarithmic models are useful but are acceptable only in low airflow, low-temperature applications.

Boyce (1965) [14], considering the sensible heating of the grain during drying, presented a model for the layer-by-layer calculation of the temperatures and moisture contents of air and grain. He used his model to simulate the drying of remoistened barley but found that the drying times predicted by his model were too long. Boyce (1966) [15] obtained improved predictions with a modified model which included an empirical expression for his volumetric heat transfer coefficient as a function of temperature and mass airflow rate.

Thompson *et al* (1968) [16] presented a similar model which incorporated a procedure to adjust the predicted values of air temperature and humidity to ensure that the predicted relative humidity did not exceed 100%. Additionally, they suggested how the model might be used for the simulation of continuous flow driers.

Henderson & Henderson (1968) [17] also obtained such a model to perform a 'sensitivity' study of the effects on their predicted values of variations in empirical constants involved in their drying rate expression and of changes in the airflow rate. These models are all based on heat and mass balances taken over a thin layer of grain in which it is assumed that conditions are constant over a given increment in time. Different types of driers have used heat and mass balance models and, in some cases, have produced satisfactory results for a variety of crops. The attainable accuracy of the predictions made using such models is, however, restricted by the assumptions usually made in their derivation.

Van Arsdel (1955) [18] was among the first to obtain such a model consisting of a system of four hyperbolic partial differential equations for simultaneous heat and mass transfer, which he presented in terms of dimensionless independent variables.

Klapp (1963) [19] presented equations for heat and mass transfer in a granular bed, for which, under simplifying assumptions, he obtained a perturbation solution in terms of modified Bessel functions. Several workers have made use of these solutions.

Ngoddy *et al* (1966) [20] used a solution of the pure heat transfer problem to simulate heat transfer in a deep bed of pea beans. Huang and Gunkel (1972) [21] presented a model for the simulation of heating and surface drying in a deep bed of onions. Their model took conduction effects into account though these were neglected in order to obtain a methodical solution to the heat transfer problem. Work begun in 1966 at Michigan State University led to the development of a number of models which are summarized in Bakker-Arkema *et al* (1974) [22] and Brooker *et al* (1974) [23]. These authors presented models for the fixed bed case and for each of the steady-state cases for crossflow, concurrent flow and counter flow drier simulation.

Spencer (1969a) [24] used a centered-difference approximation space-wise and the fourth-order Kutta-Merson technique to advance the solution to his fixed bed equations time-wise. His technique incorporates a time-step adjustment stratagem based on the truncation error estimate obtained at each step using the Kutta-Merson method, but maintains a constant space step.

Ingram (1976a) [25] presented a FORTRAN program for the solution of his fixed bed equations. He makes use of an explicit finite difference technique with a single iterative correction, in effect a crude implicit method.

Nelson (1960) [26] presented an 'analysis of batch grain-drier performance' in which he obtained an equation for the 'average drying effect by air', E, in terms of three dimensionless variables. The quantity E is defined as the mass of moisture removed from the grain per unit mass of drying air circulated through it.

Deep Bed Models

Deep bed models are of three types, viz. logarithmic, heat and mass balance, and p.d.e. models (Morey *et al*). Models are accessible and specified a much more thorough treatment in view of their greater accuracy and applicability over a wider range of grain drying problems.

Logarithmic models

Hukill presented a basic study of deep bed drying. Assuming that the (time) rate of drying at some given depth x, after time t, is proportional to the (spatial) rate of decrease in air temperature at (x, t) he obtained

$G_aC_a \; \delta T/\delta T = \rho_p \; h_{fg} \; \delta M/\delta t$ 1

Baughman *et al*. suggested the further relationship

$G_aC_a \; \delta T/\delta T = Qh_{fg} \; \delta M/\delta x$ 2

where Q represents the “rate of advance” of the drying zone, and, using above both equations

$\delta(MR)/\delta t = -1 / 1\text{-}MR(0,t) \;\; \delta(MR)/\delta x$ 3

Barre *et al* solved Eqn. assuming initial and boundary conditions of the form

$MR(0,t) = \exp(-t)$

$MR(X,0) = 1$ 4

Eqn (3) together with (4) give the velocity of the drying zone as

$dX/dt = 1/(1-e^{-t})$

They applied their model to cross-flow drying.

Partial differential equation (p.d.e.) models

The development of competent, precise and steady computational techniques, together with the increasing power of modern computing systems, has encouraged workers to device more precise grain drying models of p.d.e. type for both design and research. Newly, Laws and Parry' accessible a general mathematical framework for describing the heat and mass transfer in drying particulate solids. It was perceived by these authors that other models seeming in the prose could be considered as particular cases of their general model under further appropriate assumptions.

Convective grain drying could be represented by a general system of partial differential equations of the form

$\delta u/\delta t + A \; \delta u/\delta x + B \; \delta u/\delta y = b$

Conclusion

Mathematical modeling and computer simulation of grain drying are now widely used in agricultural engineering research. Frequent models have been projected to illustrate the heat and mass transfer processes in the basic types of convective grain drier. Most of these models have been derived under conventions that are not explicitly stated and which restrict their applications from the outset.

Moreover, the differences which exist between various models are not always clarified in the literature. With an ever-increasing demand for the accurate modeling of drying systems, it is important for the researcher to understand the basic assumptions inherent in a particular model and hence to be aware of its limitations. Additionally, the problems of obtaining satisfactory solutions for particular models have generally been given only superficial treatment.

Table-1 *Drying Models*

Model no	Model name	Model
1.	Modified page	$MR = \exp[-(kt)n]$
2.	Henderson and Pabis [27,28]	$MR = a\exp(-kt)$
3.	Logarithmic	$MR = a\exp(-kt) + c$
4.	Page	$MR = \exp(-kt\,n)$
5.	Newton	$MR = \exp(-kt)$
6.	Two terms	$MR = a\exp(-k_0 t)\exp(-k_1 t)$
7.	Two term exponentials	$MR = a\exp(-kt) + (1-a)\exp(-kat)$
8.	Wang and Singh [29]	$MR = M + at + bt^2$
9.	Approximation of diffusion	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$
10.	Verma et al.	$MR = a\exp(-kt) + (1-a)\exp(-gt)$
11.	Modified Henderson and Pabis	$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$
12.	Hii *et al.*	$MR = a\exp(-kt\,n) + c\exp(-gt^n)$
13.	Midilli *et al.*	$MR = a\exp(-kt\,n) + bt$

Application of research: The use of recreation to provide a better understanding of the drying process is now firmly established. Clearly, suitably created models can be used to help with the design of new driers and to promote the more competent use of existing driers.

Research Category: Agricultural Process Engineering

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