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A Survey on Heat Transfer in the Aerated Drying Process of Stored Grains

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Abstract. The purpose of this review is to investigate and analyze recent publications on experimental studies on mathematical models that evaluate, or suggest that such a method can be evaluated, the drying process of stored grains by aeration and how the heat transfer occurs in this process. The emphasis for this paper is on the observation of types of grains ordinarily usually used in the experimental studies, on the mathematical techniques that define the models and on the efficiency observed for these studied models. Finally, it is expected to present a paper with a synthesis consistent with the current reality that might direct subsequent research on the area of heat transfer on stored grains drying by aeration.
Keywords. Heat Transfer, Mathematical Models, Stored Grains, Drying Process, Aeration

1 Introduction

In this review will be presented the results of articles published in recent journals on experimental studies in mathematical models that evaluate the drying process of grains stored by aeration and how the heat transfer occurs in that process.

This type of research requires many factors into account. Among them, will be highlighted the different approaches achieved regarding the type of grain that is part of drying process, the type of storage to which the grain was submitted and the type of model that the procedure used to analyze the heat transfer.

In addition, there are areas related to this line of research, which are problems related to mass transfer and airflow velocity during the drying process. In some observed articles, the research was not aimed on heat transfer but used it as a parameter or a step to study these other aspects.

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2 Goal and Method

The objective of this review is to classify articles published in the last seven years in relation to the methods used in the research on heat transfer in grains submitted to an aeration drying process. In this classification, the variety of grains subjected to experimentation, the type of storage, the mathematical model used and the validation of the model will be highlighted.

For this review, reference articles are mostly related to the heat transfer problem, but four of them ([1], [3], [8] and [9]) are mentioned by the fact they are articles of research in similar areas that use the heat transfer in their models supporting and complementing the study on mass transfer or the velocity of airflow.

Thus, articles that do not deal with mathematical models based on differential equations or recursive methods, besides those that are not compatible with the study of grains, will not be part of this review.

3 Mathematical Models

In this section, the main equations that define each model observed during the review will be presented. However, they usually depend of other equations and parameters that can be verified in the reference pointed out in more detail. The observed models will be divided into two groups, models using differential equations and models using recursive equations.

3.1 Models Using Differential Equations

In this section, is shown the differential equations that define the models of the respective mentioned references. Some references may not utilize this type of model or eventually use more than one.

In reference [6], the authors used a model for the paddy columnar dryer to observe the heat transfer. The main equation that defines this model is:

$$\frac{\partial T_p}{\partial y} = -\frac{h_{cv}\left(T_a - T_p\right) - G_a\left(L_{fg} + \left(c_{pw} - c_{pl}\right)\right) T_g \left(\frac{\partial H}{\partial x}\right)}{G_p c_p + G_{pl} M}\ , \tag{1}$$

where G_p is the flow rate of grain (kg.ph^{-1}.m^{-2}), G_a is the mass flow rate of air (kg.ph^{-1}.m^{-2}), h_{cv} is the volumetric heat transfer coefficient (W.m^{-2}.°C^{-1}), c_a is the specific heat of air (kJ.kg^{-1}.°C^{-1}), c_{pl} is the specific heat of water (kJ.kg^{-1}.°C^{-1}), $c_p w$ is the specific heat of water vapor (kJ.kg^{-1}.°C^{-1}), H is the humidity (%) and L_{fg} is the latent heat of vaporization of moisture from grain (kJ.kg^{-1}). The explanation for M, T_a, T_p and T_g can be found in [6], they are determined through other differential equations.

In reference [4], the authors adopted four models, two of them related to partial differential equations and the other two related to a recursive method, which will be dealt with in the following subsection.

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The first of these models was the model of a homogeneous reactor, where the authors used in a vertical silo a partial differential equations system to observe the heat transfer. This system is shown below:

$$\begin{cases} \frac{\partial T_a}{\partial t} + \nu \frac{\partial T_a}{\partial y} = \frac{-a(1-\epsilon)\phi_m c_{pv}(T_g - T_a) + \phi_h}{\rho_a \epsilon (c_{pa} + c_{pv} W)} \\ \\ \frac{\partial T_g}{\partial t} = \frac{a(\phi_h - \phi_m (H_v + (c_{pv} - c_{pw}) T_g))}{\rho_g (c_g + M c_{pw})} \end{cases} , \tag{2}$$

where M is the grain moisture content (d.b.), a is the grain surface area/volume ratio (m^{-1}), H_v is the latent heat of water vaporization ($\mathrm{J.kg}^{-1}$), c_g is the specific heat of grain ($\mathrm{J.kg}^{-1}.\mathrm{K}^{-1}$), c_{pv} is the specific heat of water's vapor ($\mathrm{J.kg}^{-1}.\mathrm{K}^{-1}$), c_{pw} is the specific heat of water ($\mathrm{J.kg}^{-1}.\mathrm{K}^{-1}$), c_{pa} is the specific heat of dry air ($\mathrm{J.kg}^{-1}.\mathrm{K}^{-1}$), ρ_g is the specific mass of grain ($\mathrm{kg.m}^{-3}$), ρ_a is the specific mass of air ($\mathrm{kg.m}^{-3}$), ϵ is the porosity, ν is the vertical velocity ($\mathrm{m.s}^{-1}$), T_a is the air temperature (°C), T_g is the grain temperature (°C), ϕ_h is the heat flux ($\mathrm{W.m}^{-2}$) and ϕ_m is the mass flux ($\mathrm{kg.m}^{-2}.\mathrm{s}^{-1}$). The other model based on a partial differential equations system was the moving boundary model, which is shown below:

$$\begin{cases} \frac{\partial T_1}{\partial t} = a_{h1} \frac{\partial^2 T_1}{\partial y^2}, \quad y \in [0; s(t)]\,, \quad t \in [0; t_{max}] \\ \\ \frac{\partial T_2}{\partial t} = a_{h2} \frac{\partial^2 T_2}{\partial y^2}, \quad y \in [s(t); H]\,, \quad t \in [0; t_{max}] \end{cases} , \tag{3}$$

where the boundary conditions and the coupling conditions are specified in the reference [3], and a_{h1} is the constant $15.1 \times 10^{-5}\mathrm{m}^2.\mathrm{s}^{-1}$ and a_{h2} is the constant $1.01 \times 10^{-5}\mathrm{m}^2.\mathrm{s}^{-1}$.

In reference [7], the authors evaluated the heat transfer using a semi-cylindrical drying chamber with shallow depth forced-air and the Fourier's Law, which consists of a partial differential equation. The equation is shown below:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \bullet k_0 \nabla T + Q \,, \tag{4}$$

where ρ is the density of grains, k_0, is the thermal conductivity of brown rice, C_p is the specific heat of brown rice grains, Q is the amount of heat lost due to evaporation and $\partial T, \partial t$ is the variation of temperature in time.

In reference [2], the authors used deep bed dryer and a model based on a system of three partial differential equations, where the first represents the equation of conservation of mass, the second represents the equation of energy for air and in the last the equation of energy for the product. The system that defines this model is shown below:

$$\begin{cases} \rho_a \epsilon \left(\frac{\partial W}{\partial t} + u \frac{\partial W}{\partial x} \right) = (\epsilon - 1)\, \rho_p \frac{\partial M}{\partial t} \\ \\ \rho_a \left(C + C_v W \right) \left(\frac{\partial T_a}{\partial t} + u \frac{\partial T_a}{\partial x} \right) = \frac{\xi \alpha (T_p - T_a)}{\epsilon} \\ \\ \rho_p \left(C_p + C_w M \right) \frac{\partial T_p}{\partial t} = \frac{\xi \alpha}{1-\epsilon} \left(T_a - T_p \right) - \\ \qquad - \left(H_v + C_v \left(T_a - T_p \right) \right) \frac{\rho \epsilon}{1-\epsilon} u \frac{\partial W}{\partial x} \,, \end{cases} , \tag{5}$$

where C is the specific heat of dry air (J.kg^{-1}.°C^{-1}), C_p is the specific heat of grain (J.kg^{-1}.°C^{-1}), C_v is the specific heat of vapor (J.kg^{-1}.°C^{-1}), C_w is the specific heat of water (J.kg^{-1}.°C^{-1}), H_v is the latent heat of vaporization (J.kg^{-1}), M is the grain moisture content (kg$_{\text{water}}$/kg$_{\text{db}}$), T_a is the air temperature (°C), T_p is the grain temperature (°C), u is the inlet air velocity (m.s^{-1}), W is the absolute humidity of air (kg$_{\text{water}}$/kg$_{\text{dry air}}$), α is the specific surface per unit volume of grain bed (m^2.m^{-3}), ϵ is the void fraction, ξ is the convection heat transfer coefficient (W.m^{-2}.°C^{-1}), ρ_a is the density of dry air (kg.m^{-3}) and ρ_p is the density of product (kg.m^{-3}).

In [5], the mass and heat transfer processes during the drying of soya beans in a continuous cross-flow dryer with three drying stages and cooling chamber were described by a system of four order non-linear partial differential equations. The system is shown below:

$$\begin{cases} \frac{\partial T_a}{\partial t} + V_x \frac{\partial T_a}{\partial x} + V_y \frac{\partial T_a}{\partial y} = \frac{a(\epsilon - 1)}{\rho_a \epsilon} \cdot \frac{\phi_m C_{pv}(T_g - T_a) + \phi_h}{C_{pa} + C_{pv} W} \\ \frac{\partial T_g}{\partial t} = \frac{a(\phi_h - \phi_m(H_v + (C_{pv} - C_{pw})T_g))}{\rho_g (C_{pg} + M C_{pw})} \\ \frac{\partial W}{\partial t} + V_x \frac{\partial W}{\partial x} + V_y \frac{\partial W}{\partial y} = \frac{\phi_m a (1-\epsilon)}{\rho_a \epsilon} \\ \frac{\partial M}{\partial t} = -\frac{\phi_m a}{\rho_g} \end{cases} , \tag{6}$$

where M is the grain moisture content, (d.b.), W is the air humidity, a is the grain surface area/volume ratio (m^{-1}), H_v is the latent heat of water vaporization (J.kg^{-1}), C_{pg} is the specific heat of grain (J.kg^{-1}.K^{-1}), C_{pv} is the specific heat of water vapor (J.kg^{-1}.K^{-1}), C_{pw} is the specific heat of water (J.kg^{-1}.K^{-1}), ρ_g is the specific mass of grain (kg.m^{-3}), ρ_a is specific mass of air (kg.m^{-3}), ϵ is the porosity, V_x is the air velocity (m.s^{-1}), V_y is the vertical velocity (m.s^{-1}), T_a is the air temperature (°C), T_g is the grain temperature (°C), ϕ_h is the heat flux (W.m^{-2}) and ϕ_m is the mass flux (kg.m^{-2}.s^{-1}).

In [10] the authors manipulated corn grains and simulated the process of mass and heat transfer with the 3D real body-model, which is acquired by scanning the corn kernels with a high-precision medical machine. To model the heat transfer, they used the equation below:

$$\frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial t}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) + q_v = \frac{\partial}{\partial t}(\rho H) \ , \tag{7}$$

where x, y and z are the cartesian coordinates that represent the corn kernel as a $3D$ body, q_v is the heat generating rate of inner heat source (J.m^{-3}.s^{-1}), ρ is the density of corn (kg.m^{-3}), λ represents the thermal conductivity of corn (W.m^{-1}.K^{-1}), T is the temperature of corn kernel (K) and H can be determined using another equation, shown in the article, so as others details.

3.2 Models Using Recursive Methods

The only reference which used directly recursive methods to model the heat transfer among the references cited in this study was the work of Khatchatourian and Binelo [3], which used two of these models. The objects of study and the nomenclature explanation are the same as the other models of this reference in the previous subsection. The first of these models was the model of homogeneous reactor, which has as the main equation:

$$T_{g_i}^{(n+1)} = \frac{c_g \rho_g \Delta y_i (1-\epsilon) T_{g_i}^{(n)}}{c_g \rho_g \Delta y_i (1-\epsilon) + c_{pa} \rho_a \nu \epsilon \Delta t} + \frac{c_{pa} \rho_a \nu \epsilon \Delta t \left(T_{g_{i-1}}^{(n)} + T_{g_{i-1}}^{(n+1)} \right) /2}{c_g \rho_g \Delta y_i (1-\epsilon) + c_{pa} \rho_a \nu \epsilon \Delta t} \,. \tag{8}$$

The second was the model using the generalized homochronous number, which uses some results obtained in the model of partial differential equations system to calculate the average temperatures of grain (T_m) and the air (T_{a_i}) through recursive methods shown below:

$$\begin{cases} T_m = \alpha_1 T_{g_i}^{(n)} + (1-\alpha_1) T_{g_{i+1}}^{(n)} \\ \\ T_{a_i} = \alpha_2 T_{g_i}^{(n)} + (1-\alpha_2) T_{g_i}^{(n+1)} \end{cases} , \tag{9}$$

where $\alpha_1 = 0.85$ and $\alpha_2 = 0.25$ are weighting coefficients that determine the contribution of temperature $T_{g_i}^{(n)}$ obtained by minimizing the discrepancy between the measured and predicted data.

Both models can be checked in more exact detail in the corresponding reference.

4 Results of Studied Models

This section will show results obtained in papers referenced in this study that were not shown in the previous section. At the end, the table 1 shows the type of grain used in these papers as well as the type of storage used in the drying process.

In the simulation of model studied in the paper published by Nguyen, Duong and Gummert [6], the authors verified that a uniform grain temperature of 38°C can be achieved if the drying airflow is reversed at about 2/3 of drying chamber length, however, the study will continue aiming to evaluate this model in the future.

In the simulation of model studied in the paper published by Khatchatourian, Binelo, Neutzling and Faoro [4], the authors evaluated the four models analyzed and proposed, for future studies, experiments for the validation of models in other types of silos and for other grain varieties.

In the paper published by Perez, Tanaka, Hamanaka and Uchino [7], the authors evaluated the chosen heat transfer model and as conclusion, they noticed that during forced-air drying of rice grains, the grains located in the bottom of drying chamber absorbed significant amount of heat than those in the middle and topmost layers.

In the paper published by Hemis, Singh, Jayas and Bettahar [2], the authors compared the experimental results adopting the proposed model with the data obtained during the drying of wheat in deep beds. The simulation results obtained by the mathematical model were in good agreement with those obtained by experiments. This suggests that the model was evaluated.

In the paper published by Khatchatourian, Vielmo and Bortolaia [5], the researchers conclude they could evaluate the non-uniformity of temperature and grain moisture content distributions in dryers, the length of drying process and the energy efficiency for each geometry and control regime.

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Lastly, in the paper published by Zhang, Kong, Zhu, Zhang and Xu [10], the authors concluded that hot air drying is a process governed by interior mass transfer. Air velocity and temperature impose mild effects on heat transfer. Air temperature significantly affects the mass transfer process, whereas air velocity poses almost no effect, and a low velocity lessens energy consumption.

Table 1: Data analyzed in referenced articles.

Reference	Grain	Storage
[1]	Rice	Not specified
[2]	Generic Grains (Granular Porous)	Deep-bed Dryer
[3]	Soya Bean, Maize and Rice	Complex Aeration Systems
[4]	Rice	Vertical Silo
[5]	Soya Beans	Cross Flow Grain Dryers
[6]	Paddy	Columnar Dryer
[7]	Brown Rice	Shallow Depth Forced-Air
[8]	Generic Grains	Mixed-Flow Dryer
[9]	Corn and Rice	Mixed-Flow Dryer
[10]	Corn	Not specified

5 Conclusion

Observing this survey, we distinguish that results found on the process of heat transfer to rice grains are frequent, however, the type of storage for drying varies in many ways there being nothing close to uniformity.

In addition, the majority of references found used models based on partial differential equations.

Therefore, for future research in the area of mathematical modeling for heat transfer in grain drying by airflow, it is suggested the improvement of models through partial differential equations and a study that takes as a starting point results for the drying of rice grains, since these have been shown in quantity and quality in an academic perspective.

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