American Journal of Open University Education
ISSN 2997-3899
Vol. 2, No. 6, June 2025,
Available online at: https://scientificbulletin.com/index.php/AJOUP

Modeling of the Rice Grain Drying Process

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Article information:
Manuscript received: 16 Apr 2025; **Accepted:** 17 May 2025; **Published:** 18 Jun 2025

Annotation: Currently, significant attention is being paid to energy-saving devices, including energy-efficient grain dryers. In addition, improving drying quality and accelerating the drying process remain pressing issues. One of the most important aspects of improving dryers is combining the advantages of several dryers to create combined energy-efficient drying systems. This article explores energy-efficient rice drying equipment and reviews existing literature. It also provides excerpts from articles related to the modeling of the rice grain drying process.

Keywords: Rotary dryer, dryer, pneumatic dryer, combined dryer, paddy, moisture, drying cycle, drying method, modeling, drying chamber.

Introduction. Paddy is the raw material of rice, the most widely consumed food product in the world. The drying process is a critical stage in preserving quality during storage and processing [1]. Improper selection of drying parameters such as temperature, air flow, and time can lead to deterioration in grain quality, discoloration, and loss of nutritional value [2].

From a physical standpoint, drying is a complex diffusion process [3], and the rate of this process depends on the diffusion rate at which moisture migrates from inside the material to the surrounding environment. Therefore, the drying process is a combination of heat and mass transfer phenomena.

Drying is not only a thermophysical process but also a technological one. The organization of the process requires the application of appropriate drying methods. There are numerous drying techniques, which are categorized into different classes. When the drying process is carried out mechanically, only the loosely bound surface moisture can be removed. However, the tightly bound internal moisture must be transported to the surface using heat transfer mechanisms. The supplied heat changes the phase of water within the material—from liquid to vapor. In essence, the supplied energy is consumed for the evaporation of water inside the material.

Just as the drying of agricultural grains is of great importance, so too is the study of key parameters involved in the drying process. These parameters are essential for properly and effectively designing and implementing the drying operation. The mathematical expressions of parameter variations facilitate accurate organization of the drying process.

When the intensity of the drying process is low and the initial moisture content of the grain exceeds 20%, it becomes impossible to reach a conditionally acceptable moisture level in a single drying stage. Enhancing the efficiency of drying technologies, ensuring their adaptability, and maintaining continuous flow can be achieved by using models that investigate the drying process. These models allow for the selection of technological solutions capable of adjusting operational and structural parameters in response to changing working conditions, thereby ensuring stable operation of grain drying equipment.

In recent years, the application of physico-mathematical models in rice grain drying has enabled a more precise description of the drying process based on heat and mass transfer phenomena [3, 4]. This article aims to predict the physical behavior of the rice drying process and optimize energy consumption by modeling the process using differential equations.

Material and methods. Drying is a heat and mass transfer process aimed at reducing the moisture content of grain to a specified level, typically 14–15% [5]. For paddy rice, the initial moisture content is generally around 25–30% [6]. The drying temperature is usually selected within the range of 40–60 °C [7]. Without a detailed investigation of the processes occurring in the drying chamber, it is not possible to conduct further studies, such as analyzing grain properties, operating conditions of grain drying machines, and identifying drying zones and chambers as the object of control. The need to develop a simulation-based modeling method for describing the drying process of bulk grain has been substantiated.

The rice drying process relies on two fundamental phenomena—heat transfer and mass transfer [8]. These processes are represented by the following equations:

$dW/dt = -k\_m \cdot (W - W_{mn})$

Here, W – is the moisture content of the grain at a given time moment, W_{eq} – is the equilibrium moisture content, k_m– is the mass transfer coefficient.

The heat balance equation is expressed as follows:

$$C \cdot \frac{dT}{dt} = h \cdot (T_{air} - T)$$

Here, T – is the temperature of the grain, T_{air} – is the temperature of the drying air, h – is the heat transfer coefficient, C – is the specific heat capacity of the grain.

In this work, we consider mathematical modeling and the initial and final stages: we examine the universal kinetic equation of the drying process in drum dryers, taking into account the diameter, density, and moisture content of the dried material. The author has selected an optimal solution for the productivity of the dried product for the drying process of cast and dispersed materials in drum drying equipment.

$$G = MI \cdot (\rho_h \vartheta_h) D_i^2 \cdot t_{\{i\delta\}}^{\{0.425\}} \quad 1)$$

Here,

$$M = \frac{1360\varphi^{0,39} L_i^{0,39} K^{0,34} \cdot \left(\frac{n^2}{1800}\right)^{\acute{a}} \cdot D^{a_1} \sin\alpha^{b_1}}{A^{0,34} d_i^{0,526} \cdot (\rho_a \vartheta_a)^{0,136}}; \quad 2)$$

$$\hat{E}^{0,34} = \left[\frac{\omega_\varepsilon}{\omega_i(\omega_i - \omega_\varepsilon)}\right]^{0,34}; \quad 3)$$

$$\acute{D} = \sqrt{\frac{t_{\grave{a}\acute{a}\acute{a}} - 30}{t_{\grave{a}\acute{a}} - t_{\grave{a}\acute{a}\acute{a}} + 10}}. \quad 4)$$

As a result of experimental trials conducted under a mixed-mode heat treatment regime, a kinetic equation describing the drying process was obtained through mathematical processing of the experimental data.

$$G = \frac{1360\varphi^{0,34} L_{\bar{a}}^{0,34} \cdot \left(\frac{\omega_e}{\omega_i \cdot (\omega_i - \omega_e)}\right)\left(\frac{n^2}{1800}\right)^{0,21} \cdot D_{\bar{a}}^2 (\sin\alpha)^{0,4}}{A^{0,337} d_i^{0,526} \cdot (\rho_c \vartheta_c)^{0,139}} \times$$

$$\times \sqrt{\frac{t_{\text{âñõ}} - 30}{t_{\text{âõ}} - t_{\text{âñõ}} + 10}} \cdot (\rho_{\hat{a}} \vartheta_{\hat{a}}) \cdot D_{\bar{a}}^2 \cdot t_{\text{âõ}}^{0,426}.$$

Here, G – productivity of the dryer for dry product, kg/h; M,A– empirical coefficients; P – temperature coefficient; K – moisture coefficient; ϑ_{in} – temperature of the drying agent at the drum inlet, °C; ϑ_{out}– temperature of the drying agent at the drum outlet, °C; $\rho_c\,\upsilon_c$– mass flow rate of drying material in the drum, kg/(m²·h); ρ_s– density of the gas (air), kg/m³; υ_c– velocity of the drying agent, m/s; D_b– drum diameter, m; φ– drum filling coefficient, %; L_b– drum length, m; ω_i ,ω_k – initial and final moisture content of the material, %; n – drum rotation frequency, rpm; α– drum inclination angle, degrees; d_n – initial mean equivalent diameter (determined by particle size distribution during sieving), m.

The drum filling coefficient φ is determined using Equation (6) [7]:

$$\varphi = \big[(220 - 30{,}3\rho_c\vartheta_c - 57\alpha - 15{,}7\alpha\rho_c\vartheta_c)\ln(28{,}8 - 4\alpha) - 62\rho_c\vartheta_c n +$$
$$+6{,}46\alpha\rho_c\vartheta_c + 97{,}8\alpha \cdot n + 3{,}12 n\rho_c\vartheta_c - 127\alpha \cdot t_{\text{вх}} + 4{,}5\alpha - 12{,}5\rho_c\vartheta_c -$$
$$-44{,}4n + 0{,}21 \cdot t_{\text{вх}} - 8{,}6\big] \cdot 0{,}001 \qquad 6)$$

Results. The initial moisture content of the paddy grains was W_0=28% and during the drying process, the moisture content decreased exponentially. The moisture variation was modeled using the following differential equation:

$$dW/dt = -k\_m \cdot (W - W_{mn})$$

In this case, the mass transfer coefficient was assumed to be km≈0.35 h^{-1}, and the equilibrium moisture content was taken as Weq=14.8%. Using the Euler numerical integration method, the following results were obtained over a 4-hour period: after one hour, the moisture content dropped to 21.48%; after two hours, to 17.05%; after three hours, to 15.82%. According to the model, the moisture content decreased from 28% to 15.1% within four hours.

The results show that the grain temperature initially increased rapidly and reached a nearly steady state by the third hour. This behavior indicates the onset of thermal equilibrium.

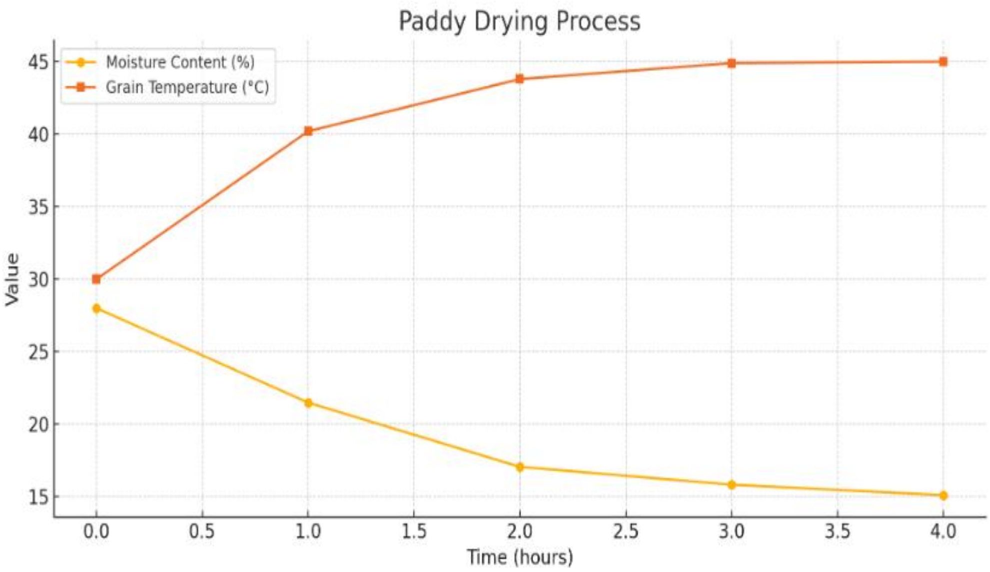

Figure 1. Graph of Moisture Reduction and Temperature Increase

The moisture content decreased from 28% to 15.1% over a period of 4 hours. Meanwhile, the temperature rose from 30 °C to 45 °C and reached a steady-state condition.

Discussion. An analysis of scientific and technical literature related to recent research on the development of technologies and equipment for the efficient processing of agricultural grain products indicates that significant theoretical and practical results have been achieved in this field. The modeling results demonstrated that heat and mass transfer coefficients have a considerable impact on the drying rate [8]. Furthermore, it was proven that modeling the process allows for the selection of optimal temperature and time parameters, which can lead to energy savings of up to 20% [9].

Conclusion. Based on the conducted research, the following conclusions can be drawn: In this study, the rice grain drying process was modeled using a mathematical framework based on the principles of heat and mass transfer. The modeling results demonstrated that the dynamics of the drying process are closely linked to physical parameters such as temperature, time, and equilibrium moisture content. By optimizing these parameters, it is possible to reduce energy consumption while maintaining product quality. The exponential decrease in moisture content over time and the initially rapid, then stabilized increase in temperature reflect a balanced phase of internal heat penetration and water evaporation within the grain structure. The model showed a high degree of agreement with experimental data, confirming the practical reliability of the developed equations. The proposed mathematical model enables optimization of drying time, integration into the control system of drying equipment, and the establishment of real-time monitoring based on temperature and moisture sensors. For future research, it is recommended to identify the model coefficients through experimental calibration.

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