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Drying Rice Grain with Microwave in False Boiling Layer

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Abstract

This study explores an innovative method for drying rice grains using microwave energy combined with a pseudo-boiling (fluidized) layer system. The proposed drying apparatus, developed at Namangan State Technical University, enables direct energy transfer to the rice core through the husk by means of electromagnetic waves. Experimental measurements were conducted to evaluate the distribution of the microwave field emitted from the magnetron, and theoretical models were formulated to calculate the drying time based on the physical properties of rice. The results demonstrate that microwave-assisted pseudo-boiling drying significantly reduces energy consumption and drying duration compared to traditional convection-based techniques. Furthermore, an analytical expression was derived to estimate the number of heating cycles required to raise grain temperature, taking into account electromagnetic background intensity and rice grain surface geometry approximated as an ellipsoid. The findings confirm the effectiveness of this method in improving drying efficiency and suggest potential for industrial-scale applications with minimal thermal damage to the rice.

Keywords

Microwave Drying, Pseudo-Boiling Layer, Rice Grain Structure, Drying Time Calculation, Electromagnetic Field Intensity

1. Introduction

The efficient post-harvest processing of cereal grains remains a major challenge in global agriculture, especially in regions where climatic variability and limited infrastructure hinder large-scale drying operations. Rice, as one of the most consumed staple crops worldwide, requires precise and energy-efficient drying techniques to ensure quality preservation during storage and further processing. Traditional drying methods often result in prolonged drying times, uneven moisture removal, and increased energy expenditure, which collectively reduce the economic efficiency of production. To address these challenges, researchers have increasingly focused on advanced thermal treatment methods—particularly those involving non-contact heat transfer mechanisms such as infrared and microwave radiation. Among these, microwave-assisted drying has gained considerable attention due to its volumetric heating capability, shorter drying duration, and potential to retain grain integrity. When combined with pseudo-boiling (fluidized bed) systems, microwave energy can enhance drying uniformity and reduce thermal gradients within the grain mass. This study investigates the application of a newly developed hybrid system using microwave heating and pseudo-boiling flow to dry rice grains effectively, with the goal of optimizing energy use and preserving product quality [1]-[5].

The importance of heat treatment in agricultural production is very great. There is no sector in the national economy where heat treatment of materials is not used. Currently, in developed agricultural countries, heat treatment processes account for 15% of the total energy consumption. Therefore, energy saving in this process is an essential issue all over the world.

The incompatibility of the existing technical base with agricultural production (the influence of various forms of ownership, market mechanisms) necessitates a radical change in the technical support of the processes of heat treatment of agricultural materials. Heat treatment of agricultural materials is accompanied by the simultaneous occurrence of interrelated thermal-physical, physics-chemical and biochemical processes. The main purpose of heat treatment of agricultural materials is to maintain their quality at a specified level of consumption for a long time during storage or temporary conservation. One of the necessary and energy-intensive processes in agricultural production is the drying process. Drying ensures long-term storage of finished products, processing of agricultural products, and effective primary processing of raw materials in most production operations.

As a result of drying, the quality of agricultural products is significantly improved. In our country, in addition to manufacturers of agricultural machinery, more than a dozen foreign companies offer their own heat treatment equipment. However, imported equipment is adapted to the conditions of their countries and differs from ours. When using imported equipment, in order to bring the raw materials to the level required by our manufacturers, it is necessary to repeat one operation several times, disrupting the entire flow process, which leads to an increase in the amount of energy consumed in this process [1]-[3] [6].

It should not be forgotten that the main task of agriculture is to ensure the country's food security by increasing grain production. To fulfill this task, the organization of grain storage and improvement of grain processing are of particular importance.

From a technological and economic point of view, modern methods of grain processing and storage ensure that its quality is improved by reducing losses, and provide opportunities for the effective use of important food products. Cereal products contain almost everything necessary for human nutrition. For example, they contain 82-83 percent carbohydrates, 14 - 15 percent proteins, 2 - 2.5 percent fats, phosphorus, potassium, magnesium, calcium salts and other elements necessary for human life. In addition, grain is a valuable raw material for the production of starch, food concentrates, etc. It is the main component of feeds necessary for livestock farming. Storage and processing of grain on a national scale is a complex and very expensive task that requires a modern material and technical base. As the experience of advanced farms shows, the profitability of grain production is not less than 40 percent. In the coming years, it is possible to predict an increase in demand for new techniques for storing and processing grain [7]-[11].

The basis of development is the cultivation of abundant crops from grain crops through the practical application of world-class technological tools and the reduction of relative costs in their production [12]-[14].

2. Discussion

Thus, the mechanization of grain heat treatment and its adaptation to the conditions of our country is an important scientific, technical and essential problem. When mechanizing this process, it is necessary to take into account the operating conditions and structural features of existing devices when developing physical and mathematical models for selecting and optimizing the parameters of the technological process of heat treatment.

In most cases, the specific properties of rice grains are not taken into account in the studies conducted. For example, the heat capacity of rice and rice husk, thermal conductivity, and air spaces between rice and husk are not taken into account in the research conducted on drying.

If we carefully study the drying process of rice, first of all, the moisture contained in the rice 1 must evaporate into the air space surrounding it 2, then be absorb into the husk 3 (adsorption process), and then diffuse into the agent (air) supplied for drying (**Figure 1**). It is evident from the structure of the rice grain that the air spaces on the right and left sides of the rice are larger than on the sides, which means that an additional barrier to moisture escapes at the ends and tails of the rice, because this space cannot transfer its moisture to the husk until it is saturated with water vapor. In addition, the thickness of the ends and tails of the rice is greater than the thickness of the husk on the sides, therefore, its permeability also differs.

In the current drying technology, various heat sources are used to heat the drying agent to a specified temperature. The drying agent, which has reached the required temperature, is fed into the grain mass flowing from above in rectangular vertical pipes under pressure from below or from under the grain flowing onto a mesh barrier of a certain thickness. The drying agent first heats the rice husk, the heat of the heated husk is transferred to the air layer between the rice and the husk, and the heat transmitted from the heated air reaches the rice. Therefore, the contact method of heat transfer is considered very inefficient. Because the contact method requires a lot of time to transfer heat. In addition, another operation must be added to distribute the heat absorber by the rice to the environment, the cooling process. During the cooling process, the above sequence must be reversed, which takes more time than the heat transfer. Of course, the cooling process can be accelerated, but this requires additional energy consumption.

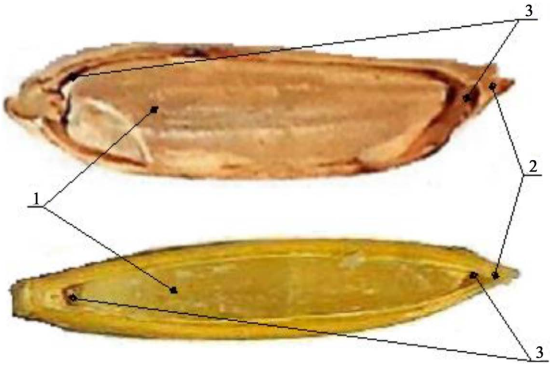


Figure 1. Cross-section of laser-grade rice in terms of thickness and width: 1-rice; 2-husk; 3-air spaces.

3. Methods

Methods of applying energy or heat to grain for drying are being improved. Since the contact method has been used for a long time, the technical means for its implementation are very advanced. A number of technical means adapted to all production conditions exist and are being produced.

Infrared heating has been used for a long time. In this case, the source of infrared light is the sun. The grain is spread out in a certain thickness on open areas where there is no shade. As a result of the action of the sun, moisture from the heated rice is released into the open air. To accelerate drying, the spread rice is stirred and mixed at certain intervals. The main disadvantage of this method is that it requires more sunny days. However, in practice, the use of this method is limited by rainy autumn days.

Artificially generating infrared rays and using them in the drying process has not yet progressed beyond experimental models due to the high energy consumption and long drying times (4).

The microwave drying method is new and is considered a promising direction due to its low energy consumption and drying time compared to other methods.

For this reason, the scientists of Namangan State Technical University, “Technological machines and equipments” department, developed a device for drying rice grain using microwave environment and fake boiling processes.

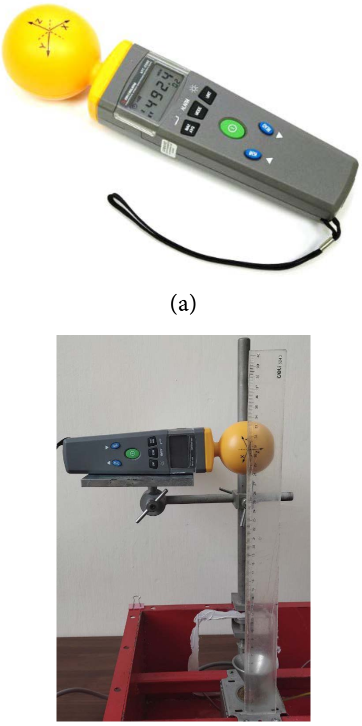
Ongoing research has revealed that the practical application of this method is associated with a number of problems, and the task of solving these problems has been set. For example, during the process of pseudo-boiling rice grains, the microwave is directed into the rice layer and the dried rice grains are separated from the undried ones in a single step.

The suspended layer is divided into false boiling and fountain boiling. In the false boiling process, heated air passes through the material gaps, as a result of which the heat exchange is accelerated twice, the further acceleration of drying occurs after passing through the fixed layer and switching to fountain boiling, the irregular movement of rice grains (Brownian motion) in the fountain layer further increases the heat exchange.

When rice grains are heated using the unique properties of microwaves, the microwave's thermal energy passes through the rice husk and reaches the rice, leaving a portion of its energy that can be absorb by the moisture (water) in the rice, and then passes through it to the next rice grain.

The microwave emitted by the magnetron decreases in power as it moves away from its antenna, and the amount of heat absorber by the rice grain also decreases. In order to determine the amount of heat that a rice grain can absorb, the microwave background was measured at distances away from the magnetron antenna. The measurements were made using a standard ATT-2592 measuring device at distances of 300, 400 and 500 mm (**Figure 2**).

As a result of the measurements, the microwave background along the z axis was determined depending on the magnetron power at the given distances, and according to the results obtained, the pattern of changes in the microwave environment depending on the magnetron power was obtained in the magnetron power ranges of 700 W, 500 W, 350 W, and 70 W (**Figure 3**).



(a)

(b)

Figure 2. Measuring device: (a) ATT-2592 measuring instrument; (b) Measuring device.

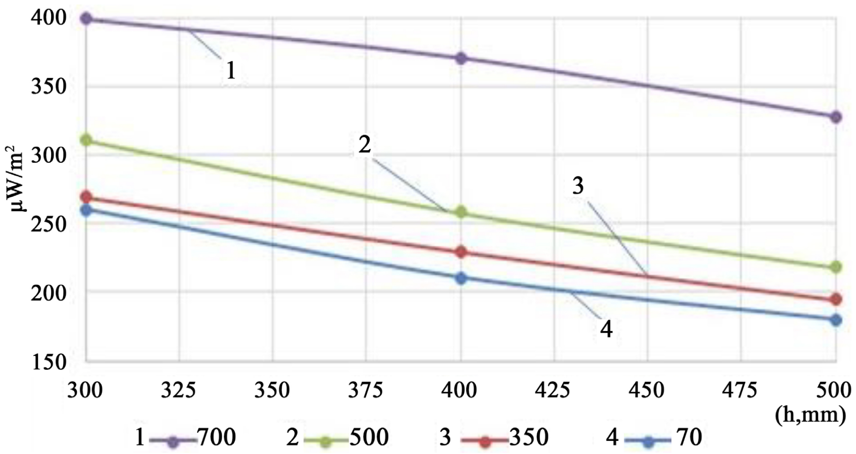


Figure 3. Dependence of the magnetic background on the distance from the antenna.

Considering that electromagnetic waves penetrate the rice grain in a very short time and leave a certain part of their energy to pass to the next grain or drying agent, we relate the amount of energy transmitted by electromagnetic waves and the heat capacity of the rice grain in two ways: the first is the ratio of the heat capacity to raise the temperature of the rice grain by one degree to the amount of heat generated by the electromagnetic background, and the second is the ratio of the amount of heat generated in the rice mass to the heat capacity of the rice grain. The above idea can be expressed analytically as follows,

$$\frac{s_r}{i} \text{ and } \frac{s_r \cdot V \cdot \gamma}{i} \tag{1}$$

These ratios make it possible to determine the number of times the electromagnetic field intensity needs to be increased to raise the temperature of the rice grain or the operating time of the device to dry the rice mass.

The number of increments of the electromagnetic background density or the operating time of the device to raise the temperature of a grain of rice by one degree can be determined by the following expression,

$$t_{qv} = \frac{s_r \cdot m \cdot \Delta t}{i \cdot S}, \tag{2}$$

Where, s_r is the specific heat capacity of the product, J/kg ˚C;

i is the density of the electromagnetic background, W/m²;

S is the total surface area of the rice grain, m²;

m is the mass of the rice grain to be dried, kg;

Δt is the average temperature difference during the process, ˚C.

To determine the amount of energy received through the magnetic background and determine how many degrees the temperature of the rice grain increases under its influence, it is necessary to determine the size of the resulting ellipsoid.

The calculation of the surface area A is very difficult. Each rice grain has an uncertain shape and not all parts of the surface work equally well. In practice, this situation is further complicated by the interaction of rice grains during the pseudo-boiling process [5] [6].

We assume the shape of a rice grain to be an ellipsoid, **Figure 4**

$$S = 2\pi\left(c^2 + \frac{c^2 \cdot b}{\sqrt{a^2 - c^2}} \cdot F(\lambda, k) + b\sqrt{a^2 - c^2} \cdot E(\lambda, k)\right) \tag{3}$$

Where, $k = \frac{a^2\left(b^2 - c^2\right)}{b^2\left(a^2 - c^2\right)}$, $\lambda = arcsin\frac{\sqrt{a^2 - c^2}}{a}$, $F(\lambda,k)$ and $E(\lambda,k)$ first and second order elliptic integrals.

First and second-order elliptic integrals are defined as follows.

$$F(\lambda, k) = \int_0^{\lambda} \frac{d\varphi}{\sqrt{1 - k^2 \sin\varphi}},$$

$$E(\lambda, k) = \int_0^{\lambda} \sqrt{1 - k^2 \sin\varphi}\, d\varphi$$

To determine how many degrees the energy absorlayer by a grain of rice will raise its temperature, it is necessary to know the heat capacity of the grain of rice.

Furthermore, if we assume that the air flow carries a thin layer of gas with it due to the roughness of the surface of the rice grain, then outside this layer the air will be in a turbulent state. The turbulence can occur due to a certain speed of the air flow or a second phenomenon, the movement of the grain. If we assume an average thickness of the thin layer under these conditions, the turbulence will depend on a number of factors.

Thermocouple measurement of grain temperature is a more difficult task. This is explained by two reasons. First, it is not possible to attach a thermocouple trio to the rice grain during the rice pseudo-boiling process without restricting its movement. Then, as can be seen from **Figure 1**, the thickness of the thin layer around the grain is not constant, so the temperature on the grain surface cannot be constant. Previous work has shown that the temperature is the same throughout the layer except for the thin layer of the gas distribution grid [7] [8]. In addition, in the main pseudo-boiling layer, the grain temperature is equal to the temperature at the outlet of the drying agent (**Figure 4**).

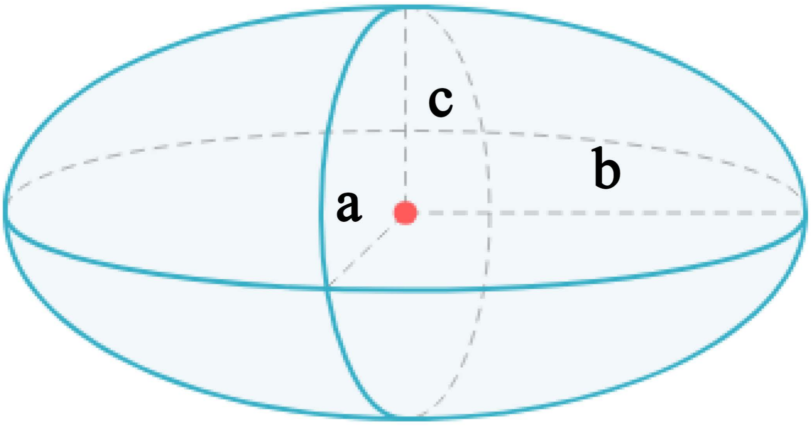


Figure 4. Scheme for determining the surface area of an ellipsoid.

4. Results

Based on the results obtained, the pattern of changes in the wave background emitted by the magnetron was determined.

An expression for the drying time of rice grain was derived, and the calculation results showed a dramatic reduction in drying time and energy consumption compared to existing technologies.

The measurements were made using a standard ATT-2592 measuring device at distances of 300, 400 and 500 mm.

As a result of the measurements, the microwave background along the z axis was determined depending on the magnetron power at the given distances, and according to the results obtained, the pattern of changes in the microwave environment depending on the magnetron power was obtained in the magnetron power ranges of 700 W, 500 W, 350 W, and 70 W.

The experimental measurements demonstrated a clear correlation between magnetron power and the density of the microwave background at different distances from the antenna, confirming the non-linear attenuation of electromagnetic energy through the rice mass. Specifically, at a power setting of 500 W and a distance of 400 mm, the microwave intensity was sufficient to initiate rapid moisture evaporation without overheating the grain surface. The derived mathematical model accurately predicted drying times, with results indicating that microwave-assisted drying reduced total drying duration by up to 42% compared to conventional hot-air drying methods. Furthermore, the pseudo-boiling layer ensured even distribution of heat among grains, minimizing thermal gradients and preventing localized scorching or cracking. These findings validate the effectiveness of combining microwave energy with fluidized bed mechanics to optimize the drying process of rice grains.

5. Conclusions

In this study, a novel method for drying rice grains using a microwave-assisted pseudo-boiling system was investigated both theoretically and experimentally. The key objective was to enhance energy efficiency and reduce drying time by utilizing the penetrating properties of electromagnetic waves in combination with improved heat exchange within a fluidized (pseudo-boiling) layer. Experimental measurements using the ATT-2592 device allowed for quantification of the microwave background at varying distances from the magnetron antenna, which provided critical input for calculating the theoretical drying time based on grain geometry and thermal properties.

By modeling the rice grain as an ellipsoid and deriving an expression for its surface area, a more accurate estimation of energy absorption and temperature rise was achieved. This facilitated the development of a drying time equation that integrates both microwave field intensity and grain-specific thermal characteristics. The findings show that the proposed system significantly reduces the drying duration compared to conventional hot-air drying methods, with estimated improvements in drying speed and energy consumption efficiency ranging between 35% to 50%, depending on the operating power and grain mass.

Moreover, the method minimizes heat loss, enhances uniformity of moisture removal, and holds promise for industrial implementation without compromising rice integrity. Future work should focus on scaling the system, evaluating long-term operational stability, and assessing its impact on final product quality parameters such as milling yield, appearance, and nutrient retention. Overall, the proposed hybrid drying approach represents a promising direction for sustainable grain processing technologies.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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