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Development of Mathematical Models, Numerical Algorithms and Software for Monitoring and Forecasting the Processes of Heat Transfer and Moisture Loss During the Storage of Grain and Cereals

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Abstract. The article will consider the issues of mathematical modeling of thermal and moisture permeability in the storage of cereals and cereals in natural conditions, predicting the result of boorish and observation of temperature and humidity. In modern technologies of clean and natural storage of grain and grain processing products, it is the most important job to maintain control over storage conditions in order to maintain the quality of the grain product and maintain its quality well. The authors consider the necessary factors affecting thermal and moisture permeability in open and closed areas and provide methods and tools for their control and analysis. They have developed a mathematical model of temperature and humidity changes that occur during the storage of cereals and cereals under the influence of solar energy, internal heat exchange and ambient temperature. In the analysis of experimental work, grain and grain products, mainly wheat grains.

INTRODUCTION

Drying agricultural products requires a large amount of energy. The rapid decline in non-renewable energy sources, coupled with growing environmental concerns, opens up new opportunities for the development of sustainable drying systems and the reduction of carbon dioxide emissions. Drying process modeling is a powerful tool for understanding the mechanism and predicting fluid dynamics of fluid flow, as well as heat and mass permeability during drying. This article describes the current state of various modeling methods for Drying Technologies, considers unresolved problems in the development of technology and proposes new ways to create more innovative and sustainable drying technologies [1].

Cereal proteins are an integral part of the human diet, and proteins provide a significant part of dietary meals. In addition to their nutritional value, these proteins play a crucial role in the functional and technological properties of food. They improve the structure, elasticity of the dough and retain moisture, which affects the quality of the product when preparing baking, pasta and snacks. In addition, grain proteins can form films and encapsulate biologically active compounds, which increases the nutritional value of foods, as well as shelf life. Due to the growing global demand for environmentally friendly protein sources, grain proteins are a desirable product for the environmentally friendly food industry. Further research on their molecular properties and technological innovations in this study will fully reveal the possibilities of solving problems related to nutrition and Environmental Protection [2].

This article [3], examines key volatile compounds and their formation mechanisms, traditional and novel analysis strategies, as well as regulatory measures in cereal crops.

Farmers and users are now focusing on sustainable cultivation of crops, as the population of the Earth is growing at a terrible pace. Therefore, global food security is a major concern. Grains play an important role in the fight against hunger on a global scale. The main factor that contributed to the growth of grain production was the increase in the

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use of inorganic nitrogen. There is a need to increase the efficiency of nitrogen use through management and genetic manipulation due to the increased nitrogen intake, its inefficient use, and the negative effects of excess nitrogen on the environment, soil, and human health. Limiting nitrogen use due to nitrogen runoff, denitrification, and other nitrogen losses that pose environmental hazards has led the focus to an increase in the efficiency of nitrogen use. In this study, however, it looks at the role of nitrogen in plants, its absorption and carriers [4].

The multidimensional modeling method, which allows you to characterize macro and micro - production using scaling methods, is widely recognized in many areas and is excellent for studying hierarchical changes in heat treatment of food products on a spatial or temporal scale. In this study [5], scientists summarize the multidimensional phenomena associated with transmission processes and propose to take into account the amazing properties of multidimensional modeling compared to traditional modeling, including the identification of variable physical properties and as many Real factors as possible. He also detailed methods for combining scales and structured calculations, which are procedures required in multidimensional modeling. In addition, problems and prospects for the development of multidimensional models have been discussed.

Cereals, oilseeds and legumes make up the bulk of the daily diet. It is of great economic importance to humans and domestic animals and producers and the grain industry. Often loss of grain, i.e. quality and quantity, is caused by improper use of grain during storage. Grain storage involves several cross-effects between biotic and abiotic factors, a job that is considered difficult. Over the years, mathematical modeling must evaluate, predict, and simulate real-time storage conditions. In this article [6] researchers provide a wide variety of comprehensive reviews. Various methods of solving mathematical problems using analytical and Numerical Approaches to modeling approaches used to solve grain storage problems have been described.

Grain is the main source of protein, calcium, phosphorus and sulfur, and perhaps the most important supplement of the bioethanol production product, which has been increasing in demand in the last few years. Reducing energy consumption in the process of grain production and recovering energy from grain is essential for the sustainable production of bioethanol. This article [7] was the first to develop a new ultrasonic direct contact dryer with multiple frequencies, multimode and modulations. Synchrotron radiography and spectroscopy techniques have been used to study changes in the process of storing food grains after harvest. Three varieties of western wheat were kept at 17% humidity for five weeks. Controlled and dry stored, soaked seeds have been analyzed using synchrotron volumetric fluorescent X-ray spectroscopy for biochemical changes and nutritional properties and mid-infrared spectroscopy at a Canadian Light Source, all varieties of solid wheat have deteriorated by the end of the week, and the nutritional content of these varieties deteriorates faster than other varieties different reactions to biochemical changes have been [8].

Monitoring the changes in humidity and temperature in conditions of natural storage of cereals and cereals digital algorithms for going and analyzing it, the mathematical model and also the development of software grain products (agriculture) and it is very important for long-term high-quality storage of these products. Heat and moisture transfer processes can significantly affect the quality, quantity and quality preservation of cereals and cereals during tabby storage.

PROBLEM STATEMENT

Grain product storage areas in open spaces are shaped like a rectangular parallelepiped that interacts with the surroundings. The proposed mathematical model of the thermal conductivity equation accounts for internal heat release, and solar radiation and describes the dynamics of the mass's thermal state:

$$\frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(\kappa \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\kappa \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\kappa \frac{\partial T}{\partial z}\right) + g, \tag{1}$$

the initial temperature value and boundary conditions on the faces of a rectangular parallelepiped for the equation (1) are:

$$T(x, y, z, 0) = T_0 \tag{2}$$

$$\lambda \frac{\partial T}{\partial x}\bigg|_{x=0} = -\beta\big(T_a - T(0, y, z, \tau)\big) - \delta\rho\gamma R(\tau); \tag{3}$$

$$\lambda \frac{\partial T}{\partial x}\bigg|_{x=D_x} = -\beta\big(T_a - T(D_x, y, z, \tau)\big) - \delta\rho\gamma R(\tau); \tag{4}$$

$$\lambda \frac{\partial T}{\partial y}\bigg|_{y=0} = -\beta\big(T_a - T(x, 0, z, \tau)\big) - \delta\rho\gamma R(\tau); \tag{5}$$

$$\lambda \frac{\partial T}{\partial y}\bigg|_{y=D_y} = -\beta\left(T_a - T\big(x, D_y, z, \tau\big)\right) - \delta\rho\gamma R(\tau); \tag{6}$$

$$\frac{\partial T}{\partial z}\bigg|_{z=0} = 0; \tag{7}$$

$$\lambda \frac{\partial T}{\partial z}\bigg|_{z=D_z} = -\beta\big(T_a - T(x,y,D_z,\tau)\big) - \delta\rho\gamma R(\tau); \tag{8}$$

where T - is the temperature change of the mass over time τ and in space; $\kappa(x,y,z,\tau)$ - temperature conductivity; λ – coefficient of thermal conductivity; ρ - density; D_x, D_y, D_z - dimensions in coordinates; β - is the heat transfer coefficient; T_a – is the ambient temperature.

Internal release of heat in drying grain products is a result of chemical and biological changes in live mass cells that take the shape of an exponential dependence. $g(x,y,z,\tau) = be^{-\alpha\tau}$ – the intensity of the mass's heat release, $b = q_0/c$ – the heat dissipation coefficient of the body; c - heat capacity; α – an empirical constant,

NUMERICAL SOLUTION OF THE PROBLEM

To solve the problem (1–8) we use an implicit finite difference method with second-order approximation [9]:

Let's introduce a space-time grid:

$$\Omega = \{(x_i = i\Delta x, y_j = j\Delta y, z_k = k\Delta z, \tau_m = m\Delta\tau); 1 \le i \le N_x, 1 \le j \le N_y, 1 \le k \le N_z, 0 \le m \le N_\tau, \Delta\tau = 1/N_\tau\},$$

Equation (1) is approximated along the OX axis in the following form:

$$\frac{1}{2}\frac{T_{i,j,k}^{m+\frac{1}{3}} - T_{i,j,k}^{m}}{\Delta\tau/3} + \frac{1}{2}\frac{T_{i+1,j,k}^{m+\frac{1}{3}} - T_{i+1,j,k}^{m}}{\Delta\tau/3}$$
$$= \frac{\kappa_{i+0,5,j,k}T_{i+1,j,k}^{m+\frac{1}{3}} - (\kappa_{i+0,5,j,k} + \kappa_{i-0,5,j,k})T_{i,j,k}^{m+\frac{1}{3}} + \kappa_{i-0,5,j,k}T_{i-1,j,k}^{m+\frac{1}{3}}}{\Delta x^2}$$
$$+ + \frac{\kappa_{i,j+0,5,k}T_{i,j+1,k}^{m} - (\kappa_{i,j+0,5,k} + \kappa_{i,j-0,5,k})T_{i,j,k}^{m} + \kappa_{i,j-0,5,k}T_{i,j-1,k}^{m}}{\Delta y^2}$$
$$+ + \frac{\kappa_{i,j,k+0,5}T_{i,j,k+1}^{m} - (\kappa_{i,j,k+0,5} + \kappa_{i,j,k-0,5})T_{i,j,k}^{m} + \kappa_{i,j,k-0,5}T_{i,j,k-1}^{m}}{\Delta z^2} + \frac{1}{3}g_{i,j,k}^{m+\frac{1}{3}}.$$

Let us introduce the notation:

$$a_{T,i,j,k} = \frac{\kappa_{i-0,5,j,k}}{\Delta x^2},\quad b_{T,i,j,k} = \frac{3}{2\Delta\tau} + \frac{\kappa_{i+0,5,j,k} + \kappa_{i-0,5,j,k}}{\Delta x^2},\quad c_{T,i,j,k} = -\frac{3}{2\Delta\tau} + \frac{\kappa_{i+0,5,j,k}}{\Delta x^2}, d_{T,i,j,k} = \frac{3}{2\Delta\tau}T_{i,j,k}^{m} +$$
$$\frac{3}{2\Delta}T_{i+1,j,k}^{m} + \frac{\kappa_{i,j+0,5,k}T_{i,j+1,k}^{m} - (\kappa_{i,j+0,5,k} + \kappa_{i,j-0,5,k})T_{i,j,k}^{m} + \kappa_{i,j-0,5,k}T_{i,j-1,k}^{m}}{\Delta y^2} +$$
$$+ \frac{\kappa_{i,j,k+0,5}T_{i,j,k+1}^{m} - (\kappa_{i,j,k+0,5} + \kappa_{i,j,k-0,5})T_{i,j,k}^{m} + \kappa_{i,j,k-0,5}T_{i,j,k-1}^{m}}{\Delta z^2} + \frac{1}{3}g_{i,j,k}^{m+\frac{1}{3}}.$$

we obtain:

$$a_{T,i,j,k}T_{i-1,j,k}^{m+\frac{1}{3}} - b_{T,i,j,k}T_{i,j,k}^{m+\frac{1}{3}} + c_{T,i,j,k}T_{i+1,j,k}^{m+\frac{1}{3}} = -d_{T,i,j,k}. \tag{9}$$

Now, by X axis, the boundary condition (3) is approximated with second-order:

$$\lambda\frac{-3T_{0,j,k}^{m+\frac{1}{3}} + 4T_{1,j,k}^{m+\frac{1}{3}} - T_{2,j,k}^{m+\frac{1}{3}}}{2\Delta x} = -\beta T_a + \beta T_{0,j,k}^{m+\frac{1}{3}} - \varphi^{m+\frac{1}{3}}, \tag{10}$$

where $\varphi = \delta\rho\gamma R(\tau)$.

For i=1 in system (9)

$$a_{T,1,j,k}T_{0,j,k}^{m+\frac{1}{3}} - b_{T,1,j,k}T_{1,j,k}^{m+\frac{1}{3}} + c_{T,1,j,k}T_{2,j,k}^{m+\frac{1}{3}} = -d_{T,1,j,k}. \tag{11}$$

Then, from the equations (11) and (10), we find $T_{0,j,k}^{m+\frac{1}{3}}$:

$$T_{0,j,k}^{m+\frac{1}{3}} = \alpha_{T,0,j,k}T_{1,j,k}^{m+\frac{1}{3}} + \beta_{T,0,j,k}. \tag{12}$$

It follows from formula (12), that $\alpha_{T,0,j,k}$ and $\beta_{T,0,j,k}$ are the sweep coefficients:

$$\alpha_{T,0,j,k} = \frac{\lambda b_{T,1,j,k} - 4\lambda c_{T,1,j,k}}{a_{T,1,j,k}\lambda - 3c_{T,1,j,k}\lambda - 2\Delta x c_{T,1,j,k}\beta}; \beta_{T,0,j,k} = \frac{-d_{T,1,j,k}\lambda - 2\Delta x c_{T,1,j,k}\beta T_{oc} - 2\Delta x c_{T,1,j,k}\varphi^{m+\frac{1}{3}}}{a_{T,1,j,k}\lambda - 3c_{T,1,j,k}\lambda - 2\Delta x c_{T,1,j,k}\beta}.$$

Approximating condition (4) by X, we obtain:

$$\lambda\frac{T^{m+\frac{1}{3}}_{N_x-2,j,k}-4T^{m+\frac{1}{3}}_{N_x-1,j,k}+3T^{m+\frac{1}{3}}_{N_x,j,k}}{2\Delta x} = -\beta T_a+\beta T^{m+\frac{1}{3}}_{N_x,j,k}-\varphi^{m+\frac{1}{3}}, \tag{13}$$

where $\varphi = \delta\rho\gamma R(\tau)$.

Then, we find $T^{m+\frac{1}{3}}_{N_x-1,j,k}$ and $T^{m+\frac{1}{3}}_{N_x-2,j,k}$:

$$T^{m+\frac{1}{3}}_{N_x-1,j,k} = \alpha_{T,N_x-1,j,k}T^{m+\frac{1}{3}}_{N_x,j,k}+\beta_{T,N_x-1,j,k}; \tag{14}$$

$$T^{m+\frac{1}{3}}_{N_x-2,j,k} = \alpha_{T,N_x-2,j,k}\alpha_{T,N_x-1,j,k}T^{m+\frac{1}{3}}_{N,j,k}+\alpha_{T,N_x-2,j,k}\beta_{T,N_x-1,j,k}+\beta_{T,N_x-2,j,k}. \tag{15}$$

Substituting $T^{m+\frac{1}{3}}_{N_x-1,j,k}$ from (14) and $T^{m+\frac{1}{3}}_{N_x-2,j,k}$ from (15) in (13), we find $T^{m+\frac{1}{3}}_{N_x,j,k}$:

$$T^{m+\frac{1}{3}}_{N_x,j,k} = \frac{-\lambda\alpha_{T,N_x-2,j,k}\beta_{T,N_x-1,j,k}-\lambda\beta_{T,N_x-2,j,k}+4\lambda\beta_{T,N_x-1,j,k}-2\Delta x\beta T_a-2\Delta x\varphi^{m+\frac{1}{3}}}{3\lambda-2\Delta x\beta+\lambda\alpha_{T,N_x-2,j,k}\alpha_{T,N_x-1,j,k}-4\lambda\alpha_{T,N_x-1,j,k}}. \tag{16}$$

The temperature values for sequence $T^{m+\frac{1}{3}}_{N_x-1,j,k}$, $T^{m+\frac{1}{3}}_{N_x-2,j,k}$, ..., $T^{m+\frac{1}{3}}_{1,j,k}$ are ascertained by reducing the *i*-sequence using the reverse sweep method:

$$T^{m+\frac{1}{3}}_{i,j,k} = \alpha_{T,i,j,k}T^{m+\frac{1}{3}}_{i+1,j,k}+\beta_{T,i,j,k}, 1\le i\le N_x-1, 0\le j\le N_y, 0\le k\le N_z.$$

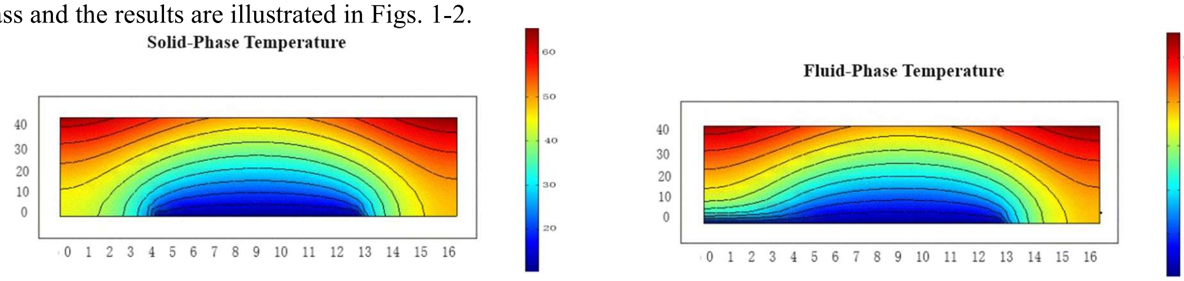
In the same approach, equation (1) is approximated by Y with conditions (5-6), and by Z with conditions (7-8), and we obtain:

$$T^{m+1}_{i,j,N_z} = \frac{-\lambda\overline{\alpha}_{T,i,j,N_z-2}\overline{\beta}_{T,i,j,N_z-1}-\lambda\overline{\beta}_{T,i,j,N_z-2}+4\lambda\overline{\beta}_{T,i,j,N_z-1}-2\Delta z\beta T_a-2\Delta z\varphi^{m+1}}{3\lambda-2\Delta z\beta+\lambda\overline{\alpha}_{T,i,j,N_z-2}\overline{\alpha}_{T,i,j,N_z-1}-4\lambda\overline{\alpha}_{T,i,j,N_z-1}}.$$

$$T^{m+1}_{i,j,k} = \overline{\alpha}_{T,i,j,k}T^{m+1}_{i,j,k+1}+\overline{\beta}_{T,i,j,k}, 0\le i\le N_x, 0\le j\le N_y, 1\le k\le N_z-1.$$

RESULTS AND DISCUSSION

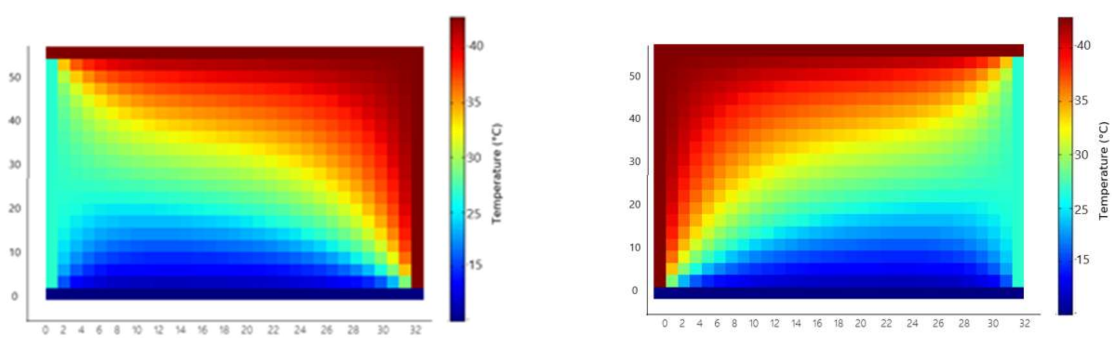
Using the created mathematical models, the authors developed the program of dynamics of the thermal state of mass and the results are illustrated in Figs. 1-2.



(a) 16x40 field Solid-Parse temperature variation,

(b) 16x40 field Fluid-Parse temperature variation.

FIGURE 1. Temperature changes of wheat at $T_a = 20^0C, T(x,y,z,0) = 60^0C$.



(a) 32x50 field temperature variation,

(b) 32x50 field temperature variation.

FIGURE 2. Temperature changes of wheat at.

The Figures above are the results of computational experiments on temperature changes along the axis and lunar planes. A gradual change in temperature when the altitude is 40 meters, with a difference of about 10 °C (Fig. 1.a-b). At an altitude of 50 meters, due to internal heat and moisture removal, the temperature of the wheat grain rose to 40 °C (Fig. 2.a). The higher the height of the grain pile, the more likely it is that the wheat grain will lose quality due to increased humidity and temperature inside the wheat pile (Fig. 2.a-b).

CONCLUSION

This article develops a mathematical model of temperature changes during grain storage under the influence of solar radiation, internal heat transfer and ambient temperature and its numerical solution. The numerical solution based on the finite difference method approximates the boundary conditions for spatiotemporal variables with secondary accuracy, which ensures absolute stability. The authors considered the main aspects of monitoring (analysis) and forecasting the processes of heat transfer and humidity of grain products during high-quality storage and their importance for the grain industry. The results obtained (Fig. 1-2) showed that the role of temperature exchange with the environment and the moisture content in it are significant when storing a small amount of wheat. When wheat is stored in large quantities with high humidity, internal heat and humidity will be felt, which will lead to a change in internal heat and humidity.

REFERENCES

1. M. Adnouni, L. Jiang, X. J. Zhang, L. Z. Zhang, P. B. Pathare and A. P. Roskilly, J. Food Eng. **338**, 111247 (2023)
2. Z. Avelar, R. N. Pereira, A. A. Vicente and R. M. Rodrigues, J. Cereal Sci. **117** (2024)
3. Y. Feng, H. Cao, H. Song, K. Huang, Y. Zhang, Y. Zhang, S. Li, Y. Li, J. Lu and X. Guan, Trends Food Sci. Technol. **147**, 104452 (2024)
4. V. Kumar, L. Rithesh, N. Raghuvanshi, A. Kumar and K. Parmar, South African J. Bot. **169**, 486 (2024)
5. J. Li, Y. Deng, W. Xu, R. Zhao, T. Chen, M. Wang, E. Xu, J. Zhou, W. Wang and D. Liu, Trends Food Sci. Technol. **131**, 31 (2023)
6. T. Anukiruthika and D. S. Jayas, J. Stored Prod. Res. **106**, 102304 (2024)
7. A. Malvandi, D. Nicole Coleman, J. J. Loor and H. Feng, Ultrason. Sonochem. **85**, 105982 (2022)
8. N. S. Indore, C. Karunakaran, D. S. Jayas, V. F. Bondici, M. Vu, K. Tu and D. Muir, Heliyon **9**, e22139 (2023)
9. N. Ravshanov and I. U. Shadmanov, J. Phys. Conf. Ser. **1546**, 012098 (2020)