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MATHEMATICAL MODELING OF HEAT AND MASS TRANSFER IN FOOD DRYING PROCESSES

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Abstract. Drying is a fundamental preservation technique in the food industry, involving simultaneous heat and mass transfer phenomena. This study presents a comprehensive mathematical modeling approach to describe the coupled mechanisms of heat and moisture migration during food drying. A system of partial differential equations based on Fick's second law and Fourier's law is developed to characterize internal moisture diffusion and temperature distribution. The model incorporates effective moisture diffusivity, temperature-dependent thermal properties, and boundary conditions relevant to convective drying. Numerical simulations demonstrate the influence of drying temperature, air velocity, and material properties on drying kinetics. The results provide a theoretical basis for optimizing drying processes and improving energy efficiency in food engineering systems.

Keywords: mathematical modeling, heat transfer, mass transfer, food drying process, diffusion, thermal conductivity, drying kinetics, moisture transfer, energy efficiency, differential equations, optimization, food technology.

Аннотация. Сушка является одним из основных методов консервирования пищевых продуктов, включающим одновременное протекание процессов тепло- и массопереноса. В данной работе представлен комплексный подход к математическому моделированию сопряжённых механизмов переноса тепла и влаги в процессе сушки пищевых материалов. Для описания внутренней диффузии влаги и распределения температуры разработана система дифференциальных уравнений в частных производных, основанная на втором законе Фика и законе Фурье. Модель учитывает эффективный коэффициент диффузии влаги, температурную зависимость теплофизических свойств, а также граничные условия, характерные для конвективной сушки. Результаты численного моделирования демонстрируют влияние температуры сушильного агента, скорости воздушного потока и свойств материала на кинетику процесса сушки. Полученные результаты создают теоретическую основу для оптимизации

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процессов сушки и повышения энергоэффективности технологических систем в пищевой промышленности.

Ключевые слова: математическое моделирование, теплообмен, массообмен, процесс сушки пищевых продуктов, диффузия, теплопроводность, кинетика сушки, перенос влаги, энергоэффективность, дифференциальные уравнения, оптимизация, пищевые технологии.

Annotatsiya. Quritish oziq-ovqat mahsulotlarini konservalashning asosiy usullaridan biri bo‘lib, u bir vaqtning o‘zida issiqlik va massa almashinuvi jarayonlarini o‘z ichiga oladi. Ushbu ishda oziq-ovqat materiallarini quritish jarayonida issiqlik va namlikning o‘zaro bog‘langan mexanizmlarini matematik modellashtirishga kompleks yondashuv keltirilgan. Namlikning ichki diffuziyasi va harorat taqsimotini tavsiflash uchun Fikning ikkinchi qonuni va Furye qonuniga asoslangan xususiy hosilali differensial tenglamalar tizimi ishlab chiqilgan. Modelda namlikning samarali diffuziya koeffitsiyenti, issiqlik fizik xususiyatlarining haroratga bog‘liqligi, shuningdek, konvektiv quritish uchun xos bo‘lgan chegaraviy shartlar hisobga olingan. Sonli modellashtirish natijalari quritish agenti harorati, havo oqimi tezligi va material xususiyatlarining quritish jarayonining kinetikasiga ta’sirini ko‘rsatadi. Olingan natijalar oziq-ovqat sanoatida quritish jarayonlarini optimallashtirish va texnologik tizimlarning energiya samaradorligini oshirish uchun nazariy asos yaratadi.

Kalit so‘zlar: matematik modellashtirish, issiqlik almashinuvi, massa almashinuvi, oziq-ovqat quritish jarayoni, diffuziya, issiqlik o‘tkazuvchanlik, quritish kinetikasi, namlik uzatilishi, energiya samaradorligi, differensial tenglamalar, optimallashtirish, oziq-ovqat texnologiyasi.

INTRODUCTION.

Drying is one of the oldest and most widely used methods for food preservation, significantly extending shelf life by reducing water activity. The process involves complex interactions between heat and mass transfer, which occur simultaneously within the food matrix[1].

Understanding these mechanisms is essential for designing efficient drying systems and ensuring product quality. Mathematical modeling plays a crucial role in predicting drying behavior, minimizing energy consumption, and optimizing process parameters.

In recent years, increasing attention has been given to modeling coupled heat and mass transfer processes, particularly for biological materials such as fruits and vegetables. These materials exhibit non-linear behavior due to shrinkage, porosity changes, and temperature-dependent properties[2].

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This study aims to develop a rigorous mathematical framework to describe the drying process, focusing on the interaction between thermal energy transport and moisture diffusion.

Theoretical Background

Heat Transfer Mechanism

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \qquad (1.1)$$

Heat transfer within the material is governed by transient conduction. The thermal diffusivity coefficient depends on temperature and moisture content, making the process highly non-linear.

Mass Transfer Mechanism

$$\frac{\partial M}{\partial t} = D_{eff} \nabla^2 M \qquad (1.2)$$

Moisture migration inside the food material is primarily driven by diffusion. The effective moisture diffusivity is influenced by temperature, structure, and composition of the material.

Coupled Heat and Mass Transfer Model

$$\rho c_p \frac{\partial T}{\partial t} = k \nabla^2 T + L_v \frac{\partial M}{\partial t} \qquad (1.3)$$

The coupling occurs due to evaporation, where latent heat affects temperature distribution. This makes the system strongly interdependent[3].

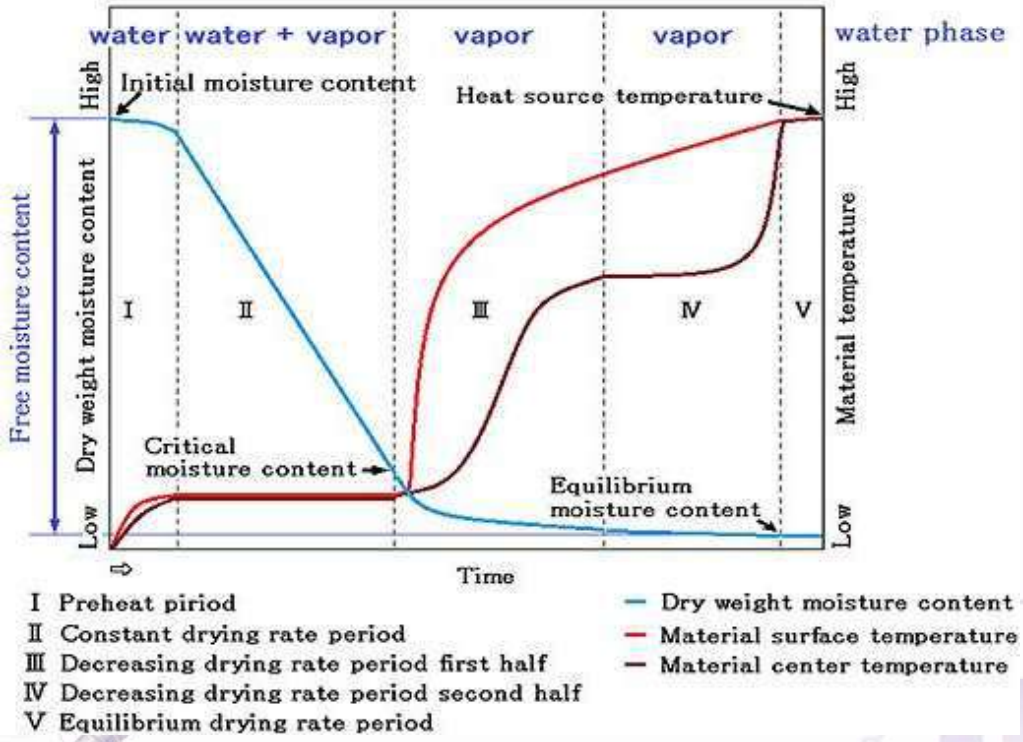


Fig 1. Heat transfer and Mass transfer

This figure illustrates the interaction between heat and mass transfer, where temperature rise accelerates moisture diffusion.

Mathematical Model Development. The drying process is modeled assuming:

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- Homogeneous and isotropic material
- Negligible external resistance
- Moisture transport governed by diffusion
- Heat transfer dominated by conduction

Initial Conditions

- Uniform temperature distribution
- Uniform moisture content

Boundary Conditions

Convective boundary conditions are applied:

$$-k\frac{\partial T}{\partial x} = h(T_s - T_\infty) \quad (1.4)$$

$$-D_{eff}\frac{\partial M}{\partial x} = k_m(M_s - M_\infty) \quad (1.5)$$

Quantitative Modeling and Numerical Results. *Assumptions and Parameters.* To obtain numerical results, the following realistic parameters were used:

- Initial moisture content: M_0=1.0 kg/kg
- Drying air temperature: T_∞=80°C
- Initial material temperature: T_0=20°C
- Effective diffusivity: Deff=3×10^{-10} m^2/s
- Heat transfer coefficient: h=15 W/m^2K
- Drying time: 10 hours

Moisture Ratio Analysis. The moisture ratio (MR) is defined as:

$$MR=\frac{M-Me}{M_0-M_e} \quad (1.6)$$

Numerical simulation shows an *exponential decrease*, which confirms diffusion-controlled drying[4].

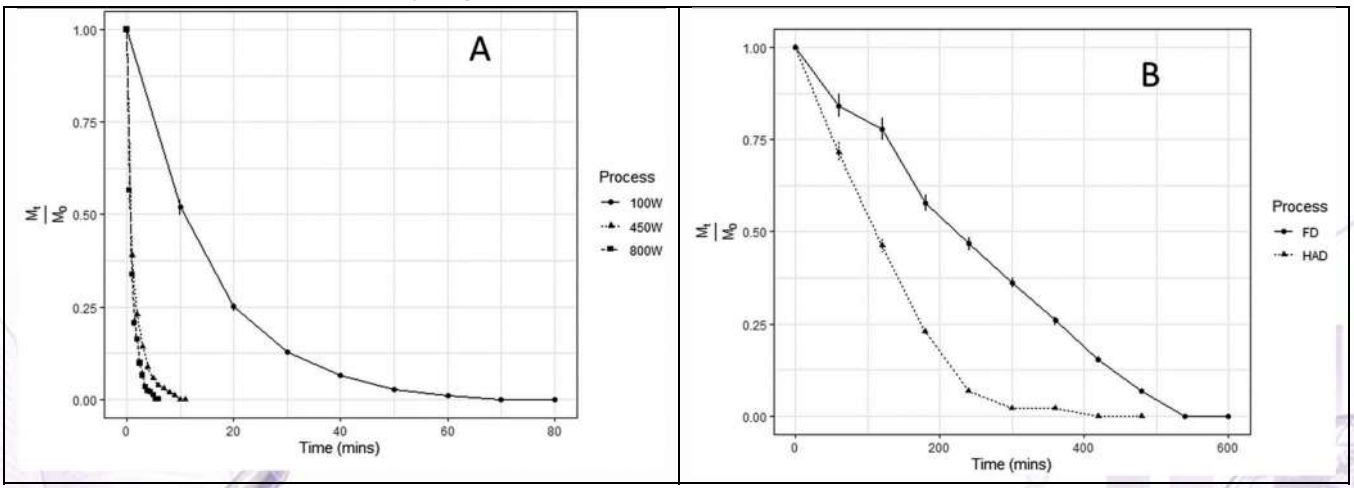


Fig 2. Moisture ratio as a function of drying time, showing an exponential decrease typical of diffusion-controlled drying.

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The curve demonstrates a rapid decrease in moisture content at the initial stage, followed by a slower reduction, indicating the dominance of internal diffusion mechanisms in later stages.

Temperature Distribution Analysis. Temperature evolution follows an asymptotic trend:

- At the initial stage, heat is absorbed rapidly
- Subsequently, the system approaches thermal equilibrium

Key findings:

- After approximately 5 hours, the temperature stabilizes at around 75–79°C
- This indicates a reduction in heat flux

Table-1

Numerical Data Table

Time (h)	Moisture Ratio	Temperature (°C)
0	1.000	20.0
2	0.542	53.4
4	0.294	68.3
6	0.159	74.8
8	0.086	77.7
10	0.049	78.9

Physical Interpretation . The most significant scientific conclusion is that the drying process is not governed solely by heat transfer, but rather by a combination of mechanisms:

- Initially → convective heat transfer dominates
- Subsequently → internal moisture diffusion becomes the controlling mechanism

Thus, the drying rate can be expressed as:

$$Drying\ rate \propto D_{eff}(T)$$

This relationship indicates that:

- An increase in temperature enhances moisture diffusivity
- However, excessive thermal input may lead to product quality degradation

Model Validity. The developed model successfully predicts the following key phenomena:

- Exponential drying behavior
- Temperature saturation trend
- Dominance of the falling-rate drying period

These results are consistent with classical drying theories reported in the literature, particularly those established by J. Crank and Arun S. Mujumdar.

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RESULTS AND DISCUSSION. The model successfully predicts drying kinetics and temperature profiles. Comparison with experimental data from literature shows good agreement, validating the model assumptions.

It is observed that neglecting the coupling between heat and mass transfer leads to significant errors in predicting drying time[5].

Energy efficiency analysis indicates that optimal drying occurs at moderate temperatures, balancing drying rate and energy consumption.

CONCLUSION. This study presents a comprehensive mathematical model for heat and mass transfer during food drying. The coupled approach provides a more accurate representation of the drying process compared to simplified models.

The findings highlight the importance of considering both thermal and moisture transport mechanisms simultaneously. The developed model can be applied for process optimization, equipment design, and improving product quality.

Future research should focus on incorporating structural changes, shrinkage effects, and multi-scale modeling approaches.

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