UDC 664 https://doi.org/10.54251/2616-6429.2025.04.0013nu

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MODELING AND OPTIMIZATION OF ENERGY CONSUMPTION IN ENERGY-INTENSIVE GRINDING PROCESSES

Abstract

This study addresses the challenge of reducing energy consumption in flour milling operations, leveraging insights from a preliminary energy audit. The audit identified the most energy-intensive processes, including grain moistening, milling, transportation, grain cleaning, as well as the operation of ventilation and microclimate control systems. The research focuses on energy consumption during grain processing at a flour mill, employing mathematical modeling and linear programming techniques to achieve this objective. A mathematical model of grain hydration was developed and implemented in a two-dimensional framework using numerical methods. The optimization of energy-intensive processes was further refined through the application of the simplex method in linear programming, incorporating constraints relevant to key stages of grain milling. The grain moistening process was optimized via a mathematical model of water diffusion, ensuring uniform hydration, eliminating the risks of over-moistening or drying, and thereby minimizing energy expenditure. By analyzing energy consumption, resources were systematically redistributed among processes, enhancing the overall energy efficiency of the enterprise. The proposed optimization measures resulted in significant reductions in energy consumption, decreased electricity costs, and improved the stability and environmental sustainability of technological operations. The findings demonstrate that combining preliminary energy audits with advanced mathematical modeling and optimization techniques constitutes an effective strategy for enhancing energy efficiency in the food processing industry.

Keywords: Preliminary energy audit, energy optimization, flour milling processes, mathematical modeling, linear programming, grain hydration, water diffusion, energy efficiency enhancement

Introduction

For most industrial enterprises, including those in the food industry, a persistent challenge in the adoption and implementation of new technologies and products is the limited availability of financial resources. Enhancing energy efficiency through technical interventions often necessitates significant capital investments. Consequently, energy-saving strategies with short payback periods (e.g., less than six months) that capitalize on the existing energy-saving potential of enterprises by monitoring equipment performance and optimizing technological processes are of considerable importance. In the food industry, the primary approaches to energy conservation focus on improving the efficiency of technological processes and minimizing energy losses during production. The initial step in implementing energy-saving measures involves analyzing the current operational state. At the enterprise level, electricity conservation is a critical priority, necessitating a thorough audit of both the technical condition of the equipment and the electricity metering systems. In flour milling, numerous processes are energy-intensive, particularly those involving mechanical, thermal, and electrical operations. Key processes requiring substantial energy expenditure include:

1. Grain drying: When raw material moisture levels are high, this process demands significant thermal and electrical energy.
2. Mechanical crushing and re-milling: These constitute the primary consumers of electrical energy within a flour mill.

3. Transportation of products: Especially pneumatic transport, which incurs substantial energy costs for compressor operations.
4. Operation of dryers or heating units: When heat treatment of flour is required.
5. Grain hydration: A critical stage in raw material preparation at a flour mill, aimed at achieving optimal moisture levels for milling. Although this process is relatively less energy-intensive compared to drying or milling, it significantly influences the efficiency of subsequent processes and the quality of the final product.

The major energy-intensive processes in flour milling include mechanical crushing, pneumatic transportation, grain cleaning, and hydration. These processes exhibit distinct energy consumption characteristics. For instance, drying and milling processes require extensive thermal and electrical energy, whereas grain hydration, despite consuming less energy, plays a crucial role in determining the effectiveness of subsequent milling operations and the quality of finished products. To optimize energy consumption, it is essential to consider both the technical condition of the equipment and the organization of technological processes. Conducting an energy audit enables the identification of critical problem areas and the development of strategies to improve energy efficiency. The implementation of energy-saving measures, however, relies heavily on the application of advanced mathematical approaches, such as linear programming, which facilitates the rational allocation of energy resources.

Existing literature highlights various methods for analyzing energy consumption and implementing measures to enhance energy efficiency in industrial enterprises. For instance, [1] explores approaches to optimizing energy use in the food industry through equipment modernization and energy audits. The study in [2] investigates grain hydration processes using mathematical modeling based on diffusion equations to enhance raw material preparation efficiency. The application of linear programming for energy cost distribution in various industrial contexts is presented in [3, 7], with specific methodologies for conducting energy audits at food enterprises. Similarly, [4] examines energy efficiency at different stages of flour milling, including grinding, transportation, and raw material processing, emphasizing modern technological solutions. Further studies, such as [5, 10], delve into water diffusion models to optimize grain hydration in the food industry, improving product quality while reducing energy costs. Methodologies for energy audits integrated with optimization techniques for energy conservation are detailed in [6]. Innovations in energy cost reduction during grain processing are discussed in [8-9], focusing on energy-saving technologies. However, comprehensive optimization of grain hydration and the allocation of energy resources across different stages of the technological cycle remains underexplored. Unlike chemical engineering processes characterized by high phase velocities, as described in [11], grain hydration primarily operates under the influence of intermolecular forces. Modeling such processes often relies on differential equations of the diffusion type, as demonstrated in [12].

This study builds on these foundations to address the gap in optimizing grain hydration and energy distribution, employing advanced mathematical modeling and optimization techniques to enhance energy efficiency in flour milling operations.

The significance of this research lies in addressing the pressing need for an integrated approach to optimizing energy consumption within flour milling enterprises. Unlike existing methodologies, this study introduces a novel framework that employs the water diffusion equation to enhance the efficiency of the grain moistening process and utilizes linear programming techniques for the rational allocation of energy resources across various technological operations. The primary objective of this research is to investigate strategies for reducing energy consumption in flour mills, leveraging a comprehensive preliminary energy audit, mathematical modeling of the grain moistening process based on the water diffusion equation, and the application of linear programming to optimize energy distribution. The proposed approach seeks to achieve significant reductions in energy expenditure without compromising the quality or efficacy of technological processes and final products. This study encompasses an analysis of energy audit findings, the development of a mathematical model for the grain moistening process, the application of linear programming to energy resource redistribution, and an evaluation of the outcomes achieved.

Materials and methods

Statement of the Linear Programming Problem.

In this section, the linear programming approach is employed to optimize energy costs in the operations of flour milling processes. The formulation of the resource consumption model is subject to the following constraints:

a) **Technological constraints**: ensuring compliance with quality standards and production volume requirements;
b) **Resource constraints**: accounting for the limitations of equipment capacity;
c) **Environmental constraints**: striving to minimize emissions and waste production.

The mathematical model is structured as a system of linear equations and inequalities that encapsulate technological, temporal, and resource-specific limitations.

The objective function of this optimization problem is defined as minimizing the total energy expenditure within the flour milling process:

$$\min Z=\sum_{i=1}^{n} c_i x_i, \tag{1}$$

where c_i— represents the cost of electricity associated with process i, x_i — denotes the amount of resource *i* consumed during the process.

The optimization problem is subject to the following constraints:

$$x_i \geq 0, \tag{2}$$

$$\sum_{i=k}^{l} c_i x_i \leq A, \tag{3}$$

$$\sum_{i=m}^{s} c_i x_i \geq B, \tag{4}$$

$$\sum_{i=1}^{n} c_i x_i \leq E_{max}, \tag{5}$$

$$\sum_{i=1}^{n} c_i x_i \geq E_{min}. \tag{6}$$

The physical and mathematical interpretations of the variables in equations (2) through (6) are as follows: *l*,*k*,*m*,*s*- represent the indices of the processes or installations that consume energy; E_{max}, E_{min} - denote the maximum and minimum permissible energy consumption levels at the plant, respectively.

Following the energy audit conducted in 2023 at the Fergana Flour Mill, data were collected on energy consumption for the primary and most energy-intensive processes. These results are outlined in the subsequent sections:

The data presented in Table 1 were utilized as input for the optimization process, implemented in Google Colab (colab.research.google.com) using Python libraries such as SciPy and PuLP.

Table 1. Initial data for optimization

Name of the process	Energy consumption (kWh) per ton (c_i)	Notes
Grain cleaning	2,25	Cleaning grain after the elevator
Moistening of grain	6,32	Calculated after hydration optimization as the minimum amount of energy
Drying grain	8,24	Conditioning after the elevator
Ventilation of industrial premises (per m^2)	8,26	Calculated according to statistical data for the last 5 years
Grain transportation	1,54	Intra-factory
Grinding grain	26,23	Average energy audit result for the previous year
Sifting flour	15,90	Average energy audit result for the previous year
Transportation of flour	2,46	Intra-factory
Flour packaging	6,28	Average energy audit result for the previous year
Heating of industrial premises (per m^2)	7,12	Calculated according to statistical data for the last 5 years
Total	81,60	

The results of the optimization are summarized in Table 2.

Table 2. Optimal energy consumption

Name of the process	Optimal energy consumption (kWh) per ton (c_i)
Grain cleaning	1,56
Moistening of grain	4,32
Drying grain	7,86
Ventilation of industrial premises (per m^2)	9,23
Grain transportation	2,10
Grinding grain	16,25
Sifting flour	12,56
Transportation of flour	1,85
Flour packaging	5,96
Heating of industrial premises (per m^2)	8,51
Total	70,20

A comparison of the final energy consumption values, both prior to and following the optimization process, indicates a reduction in energy consumption of approximately 10%.

Optimization of the hydration process

One of the critical processes in grain processing, which significantly impacts flour quality and is characterized by high energy consumption, is the hydration-moistening of grain prior to milling. As an initial step towards optimization, we have focused on optimizing this process, and the resulting optimal value is presented in Table 1. Currently, advancements in physical and mathematical sciences, alongside information technologies, are being integrated into automated process control systems (APCS). Mathematical models for grain hydration have been developed, accounting for the heterogeneity and variability in the diffusion coefficients of different grain layers. This section exemplifies the optimization of one such energy-intensive process—the grain hydration stage prior to milling.

Methods of modeling and control of the hydration process

In the works [13-15], information systems have been developed that integrate effective mathematical models and corresponding numerical methods for their implementation. Wheat varieties used for milling exhibit a wide range of shapes, geometric dimensions, water absorption capacities, and other characteristics. Therefore, the task of refining mathematical models and automated process control systems (APCS) for different regions is crucial in ensuring the production of high-quality flour.

In our view, following an energy audit, it is essential to first optimize the most energy-intensive grain preparation processes before addressing the optimization of electricity distribution across the plant. Only after optimizing these processes should the overall energy supply system be optimized using appropriate methods.

For modeling hydration, we employed the Fick equations, which describe the diffusion of moisture within the grain, and adapted them to account for the hydration process in different wheat varieties. Key factors, such as the initial moisture content, geometric parameters, diffusion coefficients, and others, are considered in the model. The Fick equation includes the molecular diffusion coefficient, denoted as D. In classical applications, D is typically treated as a constant value. However, to enhance the accuracy of the hydration modeling process, it is preferable to represent D as a variable, considering the heterogeneity of the grain's shell material and internal volume. The diffusion coefficient values can be determined through experimental studies conducted in factory laboratories or by utilizing theoretical data from existing literature.

Wheat grain exhibits anisotropic properties, meaning it has varying physical and chemical properties in different directions. As a result, diffusion can be more complex and not strictly radial. In this study, we account for the grain’s layered structure, which consists of a distinct shell, endosperm, and germ, with moisture diffusion primarily occurring in the radial direction. This is particularly relevant when there is significant variation in diffusion resistance between the layers. The boundary between these layers is sharply defined, with different diffusion properties across the layers. As the grain is fully immersed in water during the hydration process, and the water uniformly contacts the grain's surface, radial diffusion is expected to be the dominant mode of moisture movement.

In the radial diffusion model of moisture in grain, the primary variables are the radial distance r and time t. These variables describe the changes in moisture concentration over time at various distances from the center of the grain.

Results and Discussion

Radial diffusion of moisture in grain

The main equations and conditions governing the mathematical model are presented as follows:

1. The equation for radial moisture diffusion within the grain is given by:

$$\frac{\partial C(r,t)}{\partial t} = D\left(\frac{\partial^2 C(r,t)}{\partial r^2} + \frac{2}{r}\frac{\partial C(r,t)}{\partial r}\right), \tag{7}$$

where, $C(r,t)$ – represents the moisture concentration in the grain as a function of the radial distance r and time t, D is the diffusion coefficient of moisture in the grain.

2. Initial conditions: At the initial time $t=0$, the moisture concentration $C(r,0)$ within the grain can be specified as:

$$C(r,0)=C_0, \tag{8}$$

where, C_0 is the initial moisture concentration in the grain, defined as the moisture concentration upon receipt of the grain at the plant.

3. Boundary conditions: The boundary conditions are determined by the method through which moisture enters the grain. Typically, the grain is fully immersed in water, which allows us to apply the condition

$$C(R,t)=C_s, \tag{9}$$

where, R is the radius of the grain and C_s – is the moisture concentration at the grain surface

4. **Symmetry Condition at the Grain Center**: At the center of the grain, the following condition is imposed:

$$\frac{\partial C(0,t)}{\partial r} = 0. \tag{10}$$

which indicates that the moisture concentration gradient at the grain center is zero, implying that the center of the grain is a point of symmetry.

Thus, the system of equations and conditions (7)–(10) forms a complete model for the radial diffusion of moisture within the grain.

Implementation of the model by the Fourier method

To solve the system of equations (7)–(10), we employ the method of separation of variables, assuming that the solution takes the form:

$$\mathrm{C}(r,t) = U(r)T(t)\,. \tag{11}$$

Substituting equation (5) into equation (1), we obtain:

$$U(r)\frac{dT(t)}{dt} = D\left(\frac{d^2U(r)}{dr^2}T(t)+T(t)\right). \tag{12}$$

By separating the variables (7), we derive two distinct equations:

$$\frac{1}{DT(t)}\frac{dT(t)}{dt} = -\lambda, \tag{13}$$

$$\frac{1}{U(r)}\left(\frac{d^2U(r)}{dr^2} + \frac{2}{r}\frac{dU(r)}{dr}\right) = -\,\lambda, \tag{14}$$

where λ – denotes the eigenvalues associated with the Bessel function. Solution to equation (13):

$$T(t) = T_0 e^{-\lambda Dt}. \tag{15}$$

The solution to equation (8) is given by a Bessel function:

$$U(r) = AJ_0\left(\sqrt{\lambda}r\right) + BY_0\left(\sqrt{\lambda}r\right), \tag{16}$$

where J_0 и Y_0 - represent the Bessel functions of the first and second kinds, respectively. By applying the boundary conditions at the grain surface and at the center of the grain, specified in equations (9) and (10), we obtain:

$$C(R,t)=C_S\,,\ U(r)T(t) = C_{S.}, \frac{dU(0)}{dr} = 0. \tag{17}$$

Thus, the complete solution is expressed as the sum of all possible partial solutions:

$$C(r,t) = \sum_n A_n J_0(\sqrt{\lambda_n r}) e^{-\lambda_n Dt} \tag{18}$$

For a specific case, when the initial and boundary conditions are known, we can determine the values of λ_n and the constant A_n, allowing us to compute the distribution of moisture concentration both radially and over time.

The eigenvalues λ_n are determined as the squares of the zeros of the Bessel function J_0. The first few zeros of the Bessel function are:

$$\lambda_1 = (\frac{2.4048}{R})^2, \lambda_2 = (\frac{5.5200}{R})^2, \lambda_3 = (\frac{8.6537}{R})^2, \tag{19}$$

where R- is the radius of the grain cross-section at which the concentration distribution is calculated.

For use in subsequent calculations (18), the coefficients corresponding to the first three zeros of the Bessel function are given by:

$$A_1 = C_0 \frac{2}{2.4048RJ_1\,(2.4048)}, A_2 = C_0 \frac{2}{5.5200RJ_1\,(5.5200)}, A_3 = C_0 \frac{2}{8.6537RJ_1\,(8.6537)} \tag{20}$$

Fig. 1 illustrates the distribution of moisture concentration over time and across the grain layers. The experimental data are represented by the dots, while the solid lines correspond to the results obtained through the application of the model (7)–(10).

The total absolute error between the experimental data and the model's predictions does not exceed 0.05.

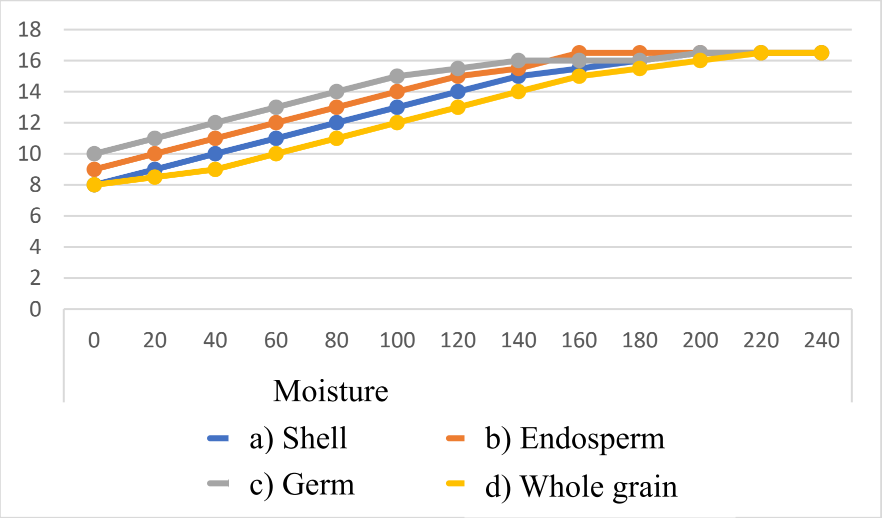

Fig. 1. Graphs depicting the temporal variation in moisture content of wheat grain across different regions: a) husk; b) endosperm; c) germ; d) whole grain.

Conclusion

Energy audits at industrial enterprises play a crucial role in identifying the most energy-intensive processes, such as grain hydration, milling, transportation, grain cleaning, as well as the operation of ventilation and microclimate control systems. These processes offer significant potential for optimization in terms of energy efficiency through the application of mathematical modeling and information technologies. In this study, the grain hydration process was optimized by developing a mathematical model, which was subsequently solved numerically to achieve the desired grain moisture concentration. Additionally, the optimal distribution of electricity across critical grain preparation processes was determined using linear programming techniques. The results of the optimization calculations indicate that energy savings of approximately 10% can be achieved solely through the optimization of energy distribution at the plant. The proposed linear programming algorithm, coupled with the developed computational program, enables the execution of numerical experiments under varying process data and parameter constraints. To further enhance the effectiveness of the proposed energy distribution optimization method at the flour mill, it is recommended to revise the constraints on process parameters to allow for more flexibility and to implement a series of organizational and technical measures aimed at optimizing the most energy-intensive processes.

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ЭНЕРГИЯНЫ КӨП ҚАЖЕТ ЕТЕТІН ҰНТАҚТАУ ПРОЦЕСТЕРІНДЕ ЭНЕРГИЯ ШЫҒЫНЫН МОДЕЛЬДЕУ ЖӘНЕ ОҢТАЙЛАНДЫРУ

Түйін

Бұл зерттеу алдын ала энергетикалық аудит нәтижелерін пайдалана отырып, ұн тарту кәсіпорындарында энергия тұтынуды азайту мәселесін қарастырады. Аудитте астықты ылғалдандыру, фрезерлеу, тасымалдау, астықты тазарту, сондай-ақ желдету және микроклиматты бақылау жүйелерінің жұмысын қоса алғанда, энергияны көп қажет ететін процестер анықталды. Зерттеу осы мақсатқа жету үшін математикалық модельдеу мен сызықтық бағдарламалау әдістерін қолдана отырып, ұн комбинатында астықты өңдеу кезінде энергияны тұтынуға бағытталған. Астықты ылғалдандырудың математикалық моделі сандық әдістерді қолдана отырып, екі өлшемді шеңберде жасалды және енгізілді. Энергияны көп қажет ететін процестерді оңтайландыру астықты фрезерлеудің негізгі кезеңдеріне қатысты шектеулерді ескере отырып, сызықтық бағдарламалауда симплекс әдісін қолдану арқылы одан әрі жетілдірілді. Астықты ылғалдандыру процесі судың диффузиясының математикалық моделі арқылы оңтайландырылды, біркелкі ылғалдануды қамтамасыз етті, шамадан тыс ылғалдану немесе кептіру қаупін болдырмады және осылайша энергия шығынын барынша азайтты. Энергия шығынын талдау арқылы ресурстар процестер арасында жүйелі түрде қайта бөлініп, кәсіпорынның жалпы энергия тиімділігін арттырды. Ұсынылған оңтайландыру шаралары энергия тұтынудың едәуір төмендеуіне, электр энергиясының өзіндік құнының төмендеуіне, технологиялық операциялардың тұрақтылығы мен экологиялық тұрақтылығының жақсаруына әкелді. Нәтижелер алдын ала энергетикалық аудиттерді озық математикалық модельдеу және оңтайландыру әдістерімен біріктіру тамақ өнеркәсібінде энергия тиімділігін арттырудың тиімді стратегиясын құрайтынын көрсетеді.

Кілттік сөздер: Алдын ала энергетикалық аудит, энергияны оңтайландыру, ұн тарту процестері, математикалық модельдеу, сызықтық бағдарламалау, астықты ылғалдандыру, судың диффузиясы, энергия тиімділігін арттыру.

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МОДЕЛИРОВАНИЕ И ОПТИМИЗАЦИЯ ЭНЕРГОПОТРЕБЛЕНИЯ В ЭНЕРГОЕМКИХ ПРОЦЕССАХ ИЗМЕЛЬЧЕНИЯ

Аннотация

Это исследование направлено на решение проблемы снижения энергопотребления на мукомольных предприятиях, используя результаты предварительного энергоаудита. В ходе аудита были выявлены наиболее энергоемкие процессы, включая увлажнение зерна, измельчение, транспортировку, очистку зерна, а также работу систем вентиляции и контроля микроклимата. Исследование сосредоточено на потреблении энергии при переработке зерна на мукомольном заводе, для достижения этой цели используются методы математического моделирования и линейного программирования. Математическая модель гидратации зерна была разработана и реализована в двумерном виде с использованием численных методов. Оптимизация энергоемких процессов была дополнительно усовершенствована благодаря применению симплекс-метода в линейном программировании, включающего ограничения, относящиеся к ключевым этапам измельчения зерна. Процесс увлажнения зерна был оптимизирован с помощью математической модели диффузии воды, что обеспечило равномерное увлажнение, исключив риск переувлажнения или сушки и, тем самым, минимизировав затраты энергии. Анализ энергопотребления позволил систематически перераспределять ресурсы между процессами, повышая общую энергоэффективность предприятия. Предложенные меры по оптимизации привели к значительному снижению энергопотребления, затрат на электроэнергию, а также повысили стабильность и экологическую устойчивость технологических операций. Полученные результаты демонстрируют, что сочетание предварительного энергетического аудита с передовыми методами математического моделирования и оптимизации представляет собой эффективную стратегию повышения энергоэффективности в пищевой промышленности.

Ключевые слова: Предварительный энергоаудит, оптимизация энергопотребления, процессы мукомольного производства, математическое моделирование, линейное программирование, гидратация зерна, диффузия воды, повышение энергоэффективности.