ISSN: 3030-3346

THE CURRENT STATE OF THEORY AND PRACTICE OF INTELLIGENT CONTROL OF DRYING PROCESSES

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K E Y W O R D S

food industry, industrial automation, theory of intelligent control, virtual factory in the food industry, and control based on neural networks and artificial intelligence

A B S T R A C T

Today, at the global level, the sustainable development of industrial production and digital transformation processes is being achieved through increasing energy efficiency, rational use of resources, and automation of production processes. The continuous growth of the world's population, rising demand for food and reserve resources, increasing electricity consumption, and the limited nature of energy resources are placing complex tasks and requirements on modern production systems. At present, ensuring energy efficiency has become one of the key strategic objectives for industrial enterprises. In particular, under highly dynamic and variable production conditions, optimizing electricity consumption and improving management efficiency in the processes of drying, storage, and processing of wheat are of great relevance.

Introduction

Intelligent control systems (ICS) encompass several key stages and periods of development in the history of automation of industrial and technological processes. The initial signs of automation in drying processes date back to the mid-19th century, beginning with the uniform distribution of heat effects on materials through the circulation of thermal energy. During this period, simple automation elements in production systems—such as electrical and mechanical automatic devices (relays, timers, contactors)—were not yet available. Drying capillary-porous colloidal materials, including grain, is a complex technological process carried out in equipment of various designs. The engineering calculation of grain dryers is based on material and heat balances; therefore, the amount of moisture removed from the material, the flow rate of the heat carrier, and the duration of the drying process are determined accordingly. However, to accelerate and automate post-harvest grain processing, new technological approaches and schematic solutions based on digital platforms are required [1, 459]. Optimizing the operating modes of grain dryers as complex dynamic systems involves formulating a control problem that considers the coordinates of a multidimensional space representing process quality, as well as constraints on permissible variations. In practice, solving such problems using fuzzy set theory has been applied very rarely. One of the main types and properties of fuzzy logic, according to widely accepted definitions, is the analysis of reasoning methods. In studying these methods, logic primarily focuses not on the content of arguments but on their form. Logic is not concerned with the truth or falsity of individual functions or conclusions; rather, it is concerned with whether the truth of a conclusion follows from the truth of the given functions [2, 77].

At present, studies are devoted to the hydrothermal properties of grain and describe its behavior during cold processing under industrial conditions, where it is necessary to measure the moisture content of the grain using instruments and process control technologies. Scientific approaches to defining precise and relatively underexplored research tasks in the field of measuring grain moisture within technological

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processes are considered, and relevant recommendations are provided. Mathematical models of the dielectric permittivity of heterogeneous moist systems and methods for improving the reliability and accuracy of monitoring material moisture using the dielectrometric method have been investigated. Issues related to the design of high-frequency methods and, on their basis, the development of capacitive measuring transducers for moisture control devices have been analyzed. In addition, the requirements for selecting methods and devices for controlling grain moisture are discussed, along with hardware tools intended for managing grain moisture in technological processes and ensuring their stable operation as part of automated process control systems [3, 7].

With the continuous growth of global food demand and the increasing requirements for food quality and energy efficiency, traditional drying technologies are facing a number of challenges. This article examines six main grain drying technologies: hot air drying, microwave drying, infrared drying, freeze drying, vacuum drying, and solar drying. The working principles, advantages, and limitations of each technology are discussed in depth, and their effectiveness in practical applications is analyzed. In response to challenges such as high energy consumption, uneven drying, and quality degradation during the drying process, the article also explores the research progress of several hybrid drying systems, including microwave–hot air combined drying systems and solar–infrared drying systems [4, 54].

Research methods and results



Fig. 1. ***Types of leguminous grains.***

Grain drying is a crucial process that directly affects its storage stability, suitability for processing, and the quality of the final product. The drying process can significantly increase shelf life and transportation efficiency by effectively reducing the moisture content of the grain, preventing the growth of bacteria and mold, and avoiding spoilage and deterioration. This is especially important in regions with high humidity, where timely drying can effectively prevent problems such as mold growth and pest infestation caused by excess moisture [5, p. 36]. In addition, a well-designed drying process can preserve the nutritional components of grain and maintain its taste and texture. Therefore, the research and application of efficient, energy-saving, and low-loss drying technologies are of great practical importance for improving the sustainability of grain production and ensuring food security. Despite the continuous development of modern grain drying technologies, many challenges remain in practical applications, affecting their efficiency, energy consumption, and the quality of the final product. One of the most common problems is low drying efficiency. Traditional drying methods often rely on convective hot air or heat conduction, which results in relatively slow drying rates, high energy consumption, and low overall efficiency.

The wheat drying process is characterized by long delays and low stability, making it difficult to ensure grain quality and relatively complex to control. Studying the mathematical model of the

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drying process has become an important tool in both domestic and international research for controlling grain drying processes. In this article, a simulation and control system was developed using the graphical programming language LabVIEW for a small modular cross-flow dryer, aimed at predicting parameter changes during the drying process and controlling these parameters [6, 54]. The system adjusts control parameters based on predicted results. Its purpose is to achieve automatic control during the drying process, ensure the accuracy and uniformity of grain moisture, increase the relative germination rate after drying, and improve the poor stability of corn moisture and low quality associated with manual control during storage.

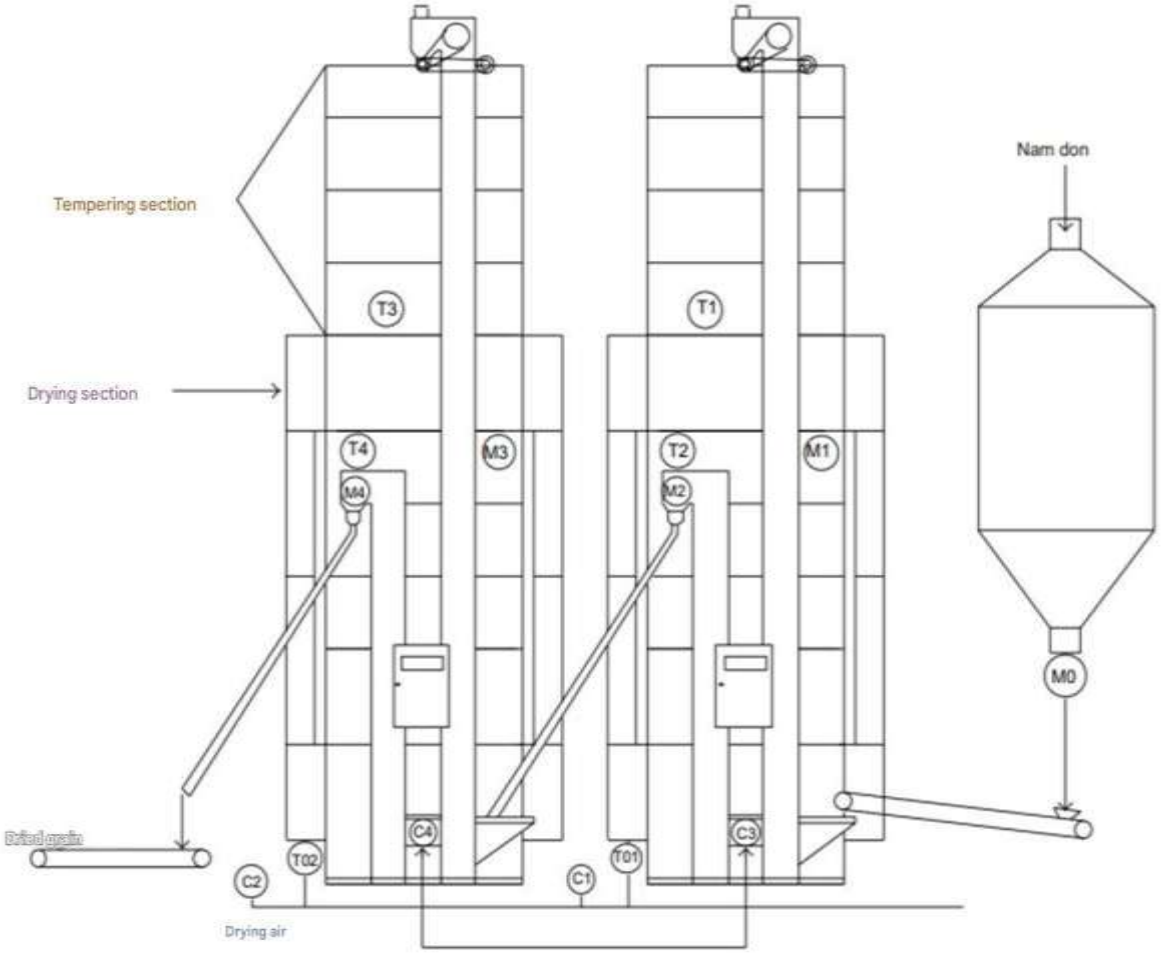


Fig. 2. ***Functional diagram of the wheat drying process.***

The drying experiment was carried out on two small 5HZ-30 type cross-flow grain dryers, which served as the basis for the predictive model. Figure 2 shows the process flow diagram of the 5HZ-30 type dryer. Developing an accurate mathematical model to predict the grain germination rate and moisture content during the drying process is essential. The schematic structure of the drying process consists of eight pentagon-shaped perforated plates, as shown in Figure 3. Corn flows downward between these perforated plates from top to bottom. Hot air passes vertically through the grain layer, removing moisture. The dryer control system includes temperature sensors T1–T4, online grain moisture sensors M0–M4, a data acquisition system, and an industrial control computer. The placement of the sensors is shown in Figure 2.

The drying system uses a distributed control system composed of a control unit computer, temperature measurement and control instruments, moisture measurement devices, control actuators, and other components. The control unit ensures data exchange between temperature measurement and control instruments (T01, T02), moisture measurement devices, and control actuators (C1–…). Communication is carried out via an Ethernet data bus. The control unit can receive data from temperature and moisture measurement

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instruments and transmit it to the PLC. To provide a large amount of measured data for the simulation system, real-time sensor data is used, and technical forecasting is adjusted for subsequent production processes [7, p. 23]. Artificial neural networks are well-known tools for controlling complex, nonlinear chemical-biological systems. They are capable of providing intelligent control methods both under normal conditions and in the presence of technological faults. In 2003, a group of Chinese researchers proposed methods for optimizing neural network topology to forecast the strength (viability) of wheat and other leguminous seeds. The model structure is as follows:

$$\frac{M-M_e}{M_0-M_e} = exp(-kt^N) \qquad (1.1)$$

Above, the grain balance equation is formulated, where **M** represents the average moisture content of the grain, **Me** is the equilibrium moisture content, and **M₀** is the standard (initial) moisture content.

The heat balance equation is expressed as follows:

$$\frac{dH}{dx} = \frac{p_g}{G_a} \cdot \frac{dM}{dt} \qquad (1,2)$$

From equations (1) and (2), the heat transfer equation is derived.

$$\frac{d\Theta}{dt} = \frac{ha(T-\Theta)}{p_g C_g + p_g C_w M} + \frac{h_{fg} + C_v(T-\Theta)}{p_g C_g + p_g C_w M} G_a \frac{dH}{dx} \qquad (1,3)$$

From equations (1) and (3), the heat balance equation is obtained.

$$\frac{dT}{dx} = -\frac{ha(T-\Theta)}{G_a(C_a + C_v H)} \qquad (1,4)$$

Here, **k** is the drying constant, and its value is determined as follows: ($k=1.091x10^2 + 2{,}767x10^{-6}T^2 + 7.286x10^{-6}TM_0$), Here, **N** is the second drying constant ($N = 0.5357 + 1.41x10^{-5}M_0^2 + 5.183x10^{-5}T^2$), Here, **t** is the drying time (in minutes), **T** is the air temperature, **H** is the air humidity, **h** is the convective heat transfer coefficient, $\mathbf{C_a}$ is the specific heat of dry air, $\mathbf{C_g}$ is the specific heat of dry grain, $\mathbf{C_w}$ is the specific heat of water, $\mathbf{C_v}$ is the specific heat of steam, and $\mathbf{G_a}$ is the air flow rate.

Based on the above parameters, the standard model of grain drying is expressed as follows:

$$Q = 1 - \frac{1}{[1 + exp(-z)]} \qquad (1,5)$$

It takes the following form.

Here, $z = A + BT^a + Ct^b + DM^y$ where **A, B, C, D** represent the real-time values of grain temperature at different measurement points, and **a, b, y** are the corresponding variation coefficients associated with the actual temperature conditions.

The drying models of grain layers consist of equations ranging from (1.1) to (1.5) and include five real-time variables, namely the average moisture content of the grain **M**, the grain temperature **y**, the air temperature after passing through the grain layer **T**, the moisture content of the hot air **H**, and the germination rate **Q**. The moisture content of the grain **M** can be obtained from equation (1.1). Through this model, it has become possible to reduce technical prediction errors in controlling the drying process by using five key variables of the grain drying model. This is achieved by collecting real-time measurement data from instruments and, based on this information, evaluating and predicting subsequent system states.

Conclusions

Within the scope of this research work, the critically analyzed materials reflect the current state of both the theory and practice of multi-component drying processes. They also make it possible to clarify the objective of developing scientific and methodological foundations for the improved control of grain drying. The aim of the research is to develop intelligent control systems for the wheat drying process, to mathematically model them, to test them experimentally, and to implement them in practice. In order to achieve this goal, the following relatively underexplored research tasks must be carried out:

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- development of mathematical models of the drying process dynamics for calculating the control system;
- development of a program-logical control system for the operating modes of a shaft drying column.

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