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HISTORY OF THEORY AND AGRICULTURAL MATERIALS DRYING EQUIPMENT DEVELOPMENT

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ABSTRACT

Drying is a key post-harvest processing operation for agricultural produce, reducing moisture content to levels required for safe, long-term storage. This study aims to systematize the historical evolution of the theory, technology, and equipment associated with drying plant-based agricultural materials, assess the current state of this scientific and technical field, and identify prospects for future development. To achieve these objectives, the study employs methods of systems analysis, scientific abstraction, and a comprehensive approach, alongside a review of literature and a synthesis of both established and cutting-edge technological solutions.

The study identifies the key stages in the evolution of drying-ranging from natural and empirical moisture removal methods to scientifically grounded technologies and automated drying systems. It analyzes the development of the process's theoretical foundations, covering heat and mass transfer principles, drying kinetics, thermo-moisture conductivity, and the properties of moisture within agricultural materials. The study systematizes the main types of drying equipment and approaches to establishing grain drying regimes. It determines that modern advancements in drying technology aim to ensure product quality while reducing energy consumption through automation, heat recovery, optimization of drying agent flow, and the use of hybrid technologies and alternative energy sources. Furthermore, the study substantiates the potential of mathematical modeling and adaptive process control for enhancing both the technological and energy efficiency of drying operations.

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ІСТОРІЯ РОЗВИТКУ ТЕОРІЇ ТА ТЕХНІЧНИХ ЗАСОБІВ СУШІННЯ СІЛЬСЬКОГОСПОДАРСЬКИХ МАТЕРІАЛІВ

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АНОТАЦІЯ

Сушіння є одним із основних технологічних процесів післязбиральної обробки сільськогосподарської продукції, що забезпечує зниження її вологості до рівня, необхідного для тривалого та безпечного зберігання. Метою дослідження є систематизація історичних етапів розвитку теорії, технології та технічних засобів сушіння рослинних сільськогосподарських матеріалів, визначення сучасного стану цього науково-технічного напряму та окреслення перспектив його подальшого розвитку. Для досягнення поставленої мети використано методи системного аналізу, наукової абстракції, комплексного підходу, аналізу літературних джерел та синтезу відомих і новітніх технологічних рішень.

У результаті дослідження встановлено основні етапи еволюції сушіння – від природних та емпіричних способів видалення вологи до науково обґрунтованих технологій і автоматизованих сушильних комплексів. Проаналізовано становлення теоретичних основ процесу, пов'язаних із закономірностями тепло- і масоперенесення, кінетикою сушіння, термовологопровідністю та властивостями вологи у сільськогосподарських матеріалах. Систематизовано основні типи сушильних установок і підходи до формування режимів сушіння зерна. Визначено, що сучасний розвиток сушильної техніки спрямований на забезпечення якості продукції за одночасного зниження енергетичних витрат шляхом автоматизації, рекуперації теплоти, оптимізації руху сушильного агента, застосування гібридних технологій та альтернативних джерел енергії. Обґрунтовано перспективність математичного моделювання та адаптивного керування процесом сушіння для підвищення його технологічної й енергетичної ефективності.

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CURRENT STATE OF THE ISSUE AND PROBLEM STATEMENT

The history of human civilization is inextricably linked to the need to obtain, process, and store food products. These processes became particularly significant following the transition from a hunter-gatherer lifestyle to agriculture and animal husbandry – a shift that began approximately 10,000 to 12,000 years ago during the Neolithic Revolution. The cultivation of grains and other crops presented humanity with a fundamentally new challenge: the need to preserve the harvest over extended periods, particularly during times when food production was impossible (*Ansu Sara Eapen et al., 2025*).

Drying has long been one of the oldest yet most effective methods for preserving plant-based produce. By utilizing solar energy and airflow to reduce the moisture content of grains, fruits, berries, and other materials, it was possible to slow down the processes of spoilage. Although early humans lacked a scientific understanding of heat and mass transfer, they empirically discovered a fundamental principle: reducing moisture content extends the shelf life of produce. Thus, the practice of drying emerged long before the development of a scientific theory explaining the process.

Archaeological and historical research indicates that even the early agricultural cultures of the Middle East, which developed around the 8th–7th millennia BCE, had specialized structures and containers for storing grain. Grain pits, barns, and other storage facilities have been discovered in ancient agricultural settlements, designed to protect supplies from atmospheric moisture and pests. Simultaneously, simple post-harvest grain processing techniques – cleaning, drying, and sorting – were developed (*Iskovich – Lototskyi & Sevostyanov, 2022*).

Significant advancements in the technology of processing and storing agricultural produce were achieved by the early agrarian civilizations of Ancient Egypt, Mesopotamia, India, and China (*Jun Wang & Hong-Wei Xiao, 2024*). The emergence of centralized states and the expansion of grain production necessitated the creation of substantial food reserves. In Ancient Egypt, for instance, grain was cleaned and dried after harvesting and threshing before being stored in specialized granaries. While the development of irrigation-based agriculture in the Nile Valley ensured abundant harvests, it simultaneously created the challenge of organizing large-scale post-harvest processing and storage.

Ancient Greece and the Roman Empire played a significant role in the development of agricultural technologies. The ancient Roman writer and agronomist Marcus Porcius Cato, in his treatise *De agri cultura* (2nd century BC) – followed later by Marcus Terentius Varro, Columella, and Pliny the Elder – described methods of farming, grain processing, and storage organization. Columella's writings, in particular, addressed the protection of grain against moisture and pests. Although these recommendations were based primarily on practical experience, they attest to the gradual accumulation of systematized knowledge regarding post-harvest crop processing.

Throughout the Middle Ages, the primary methods for storing agricultural produce remained largely conventional. Grain was kept in barns, bins, underground pits, and specialized granaries, utilizing natural ventilation and the periodic turning of the grain mass. Storage structures adapted to local climatic conditions evolved in various regions of the world. At the same time, traditional techniques for drying fruits, vegetables, grain, medicinal plant materials, and other products were being refined.

A significant milestone in technological development was humanity's gradual mastery of the controlled use of thermal energy. While natural drying relied on solar radiation, temperature, humidity, and air movement, the use of fire made it possible to generate artificially heated air. It was this technological shift that laid the foundation for the transition from natural to artificial drying. In the early stages, heating was achieved directly by fire, with the products placed either above the heat source or in specially designated areas.

The continued development of crafts and trade – and, in particular, the scientific and technological revolution of the 18th and 19th centuries – radically transformed the nature of post-harvest agricultural processing. The mechanization of farming led to increased labor productivity and a rise in grain volumes requiring rapid cleaning, transport, drying, and storage. This created a need to shift from manual operations to mechanized technological processes.

The 19th century marked the period when industrial drying technologies took shape. Specialized drying unit designs emerged in which the heat source, drying medium, material, and flow direction were viewed as components of a unified technological process. Chamber, rotary, shaft, and other types of dryers were

developed concurrently. Advancements in steam engines, heat-generating units, and ventilation equipment created the technical prerequisites for intensifying the drying process.

Alongside the development of technical equipment, the scientific foundations of the process were being established. Research into heat exchange and heat transfer – actively pursued during the 18th and 19th centuries – was of fundamental importance to the future theory of drying. The works of Jean-Baptiste Joseph Fourier, Sadi Carnot, James Prescott Joule, William Thomson, and other scientists laid the groundwork for the modern theory of thermal processes. Fourier's law of heat conduction, formulated in the early 19th century, was of particular significance, becoming one of the fundamental principles in the mathematical description of heat transfer.

The study of mass transfer and diffusion processes represented a significant area of scientific development. The scientific foundations of diffusion were established in the 19th century, notably through the work of Adolf Fick, who formulated the laws of diffusion in 1855. These principles subsequently became a crucial theoretical basis for describing moisture movement within a material during drying.

At the turn of the 20th century, knowledge regarding heat transfer, diffusion, gas dynamics, and the properties of moist materials was gradually consolidated into an independent scientific foundation for the theory of drying. Research into evaporation and moisture transport processes enabled a shift from the empirical determination of drying schedules to the identification of the principles governing changes in material moisture content over time. Work on the theory of heat and mass transfer played a significant role in this process, subsequently serving as the foundation for the design of drying systems.

In the 20th century, the development of agricultural mechanization and electrification led to rapid improvements in post-harvest grain processing machines. Integrated processing lines emerged that combined cleaning, sorting, transport, drying, and storage into a single system. Shaft and drum dryers became widespread, followed by recirculation, conveyor, pneumatic, and fluidized bed dryers (*Ayman Ibrahim et al., 2023*).

The scientific substantiation of grain drying regimes is of particular importance. Studies of the process kinetics have made it possible to establish the dependence of the moisture removal rate on the temperature and relative humidity of the drying agent, its flow velocity, the initial grain moisture content, the material layer thickness, and the grain's physicochemical properties. Concepts regarding drying periods, critical moisture content, equilibrium moisture content, and bound versus free moisture forms were also developed.

In the second half of the 20th century, the primary focus in the development of drying technologies gradually shifted from simply increasing throughput to process optimization. Rising energy costs and stricter grain quality requirements drove an active search for ways to reduce specific energy consumption. Practices such as heat-transfer medium recirculation, heat recovery, multi-stage drying regimes, and the use of advanced heat generators and automatic control systems became widespread.

At the present stage, the drying of agricultural materials is viewed as a complex, interconnected process of heat and mass transfer that must ensure not only the target final moisture content but also the preservation of the material's physical, technological, and biological properties. Modern drying complexes are equipped with systems for the automatic control of temperature, humidity, and drying flow rates, while digital technologies enable adaptive control of operating modes based on material properties and current process parameters.

Thus, the historical development of agricultural product processing and storage can be viewed as a progressive evolution from simple empirical methods of crop preservation to complex, scientifically grounded technological systems. Drying plays a pivotal role in this process, as moisture control is a decisive factor in ensuring the safe, long-term storage of a wide range of plant-based products. The evolution of drying methods, ranging from the use of solar heat to automated drying complexes, reflects the broader trend in agricultural engineering: a shift from manual operations and simple designs to mechanized, energy-efficient, and intelligently controlled machinery.

The aim of the study is to examine and systematize the historical milestones and stages in the development of scientific thought regarding the theory and practice of drying agricultural plant materials, to highlight the specific features of the current state of the field, and to identify avenues for the further development of this scientific and technical area.

MATERIALS AND METHODS

To investigate and synthesize the history of the methodology regarding the evolution of scientific concepts concerning the drying of agricultural plant materials on farms, the study employed methods involving the systems analysis of technical data, the investigation and substantiation of existing drying technologies and equipment, and the synthesis of cutting-edge ideas. Methods of scientific abstraction and a comprehensive approach were also utilized; a review of the literature was conducted, and artificial intelligence was applied to systematize the dataset.

RESULTS AND DISCUSSION

Drying is the primary technological process for bringing agricultural produce (specifically grain and seeds) to a stable state. Only after all excess moisture has been removed from the freshly harvested grain mass and the grain has been dried can reliable long-term storage be ensured..

Drying involves removing any liquid from the material, thereby increasing the relative content of the dry matter. It is known that in dry grain mass all living components, except pests and insects, are in a state of anabiotic state. Storing grain in a dry state is the primary method for maintaining high seed viability across grain batches of all crop types, as well as preserving the quality of food-grade grain during long-term storage.

All grain drying methods take into account sorption characteristics and other properties. As a material to be dried, grain is a living organism with a capillary-porous structure. The fruit coats of the seeds are permeated by capillaries and are therefore permeable to water vapor. Conversely, the seed coats and the aleurone layer are relatively impermeable to water vapor; improper drying conditions can cause the grain to swell due to the trapped water vapor accumulating within the endosperm. In addition, the embryo contains very temperature-sensitive water-soluble proteins – albumins. At temperatures above 41–42°C, the proteins in the germ (for instance, in wheat) denature, meaning the seeds lose their viability. Gluten proteins are more heat-resistant, however, the heating temperature of normal, strong and weak elastic gluten of strong wheat should not exceed 50, 45 and 55 °C, respectively..

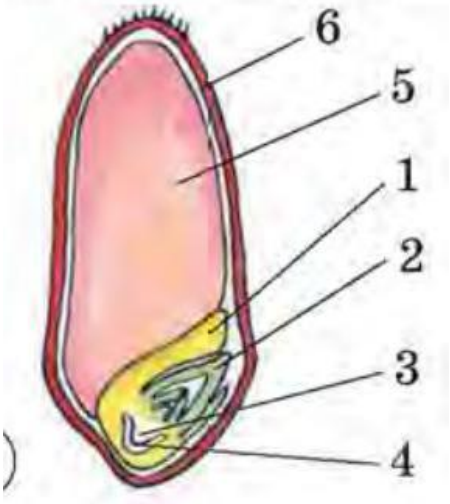

Fig. 1 – Structure of a wheat seed: 1 – cotyledon; 2 – embryonic bud; 3 – embryonic stem; 4 – embryonic root; 5 – endosperm; 6 – seed coat (in wheat seeds, it is fused with the fruit wall)

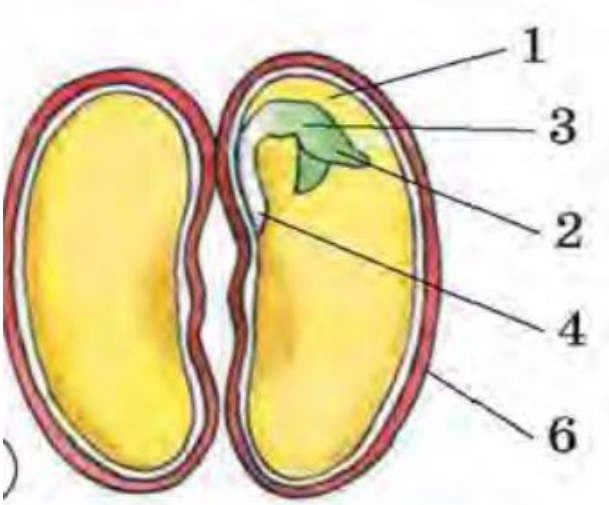

Fig. 2 – Structure of a bean seed: 1 – cotyledon (bean seeds have two); 2 – embryonic bud (plumule); 3 – embryonic stem (hypocotyl); 4 – embryonic root (radicle); 5 – endosperm; 6 – seed coat

Drying is a complex technological process involving heat and mass transfer; it must preserve the grain's inherent properties, which is achievable only when optimal process parameters are maintained. Thus, during drying, the thermodynamic and thermophysical properties of the grain, in particular heat capacity and thermal conductivity, constantly change. Three methods of grain drying (dehydration) are employed: thermal (including vacuum drying), sorption (contact) drying, and mechanical drying (pressing or centrifugation). Thermal drying is the most common method, followed by sorption drying, while mechanical drying is used

only in washing machines at flour mills. During thermal drying, liquid converts into vapor, a phase change that consumes thermal energy. The drying process relies on the grain's ability to evaporate moisture from its surface, provided that the water vapor pressure within the grain exceeds the water vapor pressure of the surrounding air.

- During grain drying, the following physical phenomena occur: - heat transfer from the drying agent to the grain; - movement of moisture from the inner layers of the grain to the surface layers; - evaporation of moisture from the grain surface and its diffusion into the surrounding environment; - movement of moisture in the presence of a temperature gradient with heat flow as a result of thermal and moisture conductivity

Drying regimes involve establishing conditions that ensure maximum dryer productivity while fully preserving grain quality. A drying regime encompasses the recommended temperature of the drying agent and the maximum permissible grain heating temperature. It also requires monitoring the total drying time and specifying the number of passes through the dryer or the number of drying cycles. The drying regime is determined by the crop (type of grain or seed), initial grain moisture content, intended use, grain quality, and the design and type of the grain dryer.

The operating mode is selected based on the grain dryer's design. Various types of dryers are suitable for the process: continuous-flow and recirculation shaft dryers, column dryers, and stationary or mobile bin dryers. Key considerations include adhering to the specific drying regime for each crop, preserving grain quality, ensuring process productivity, and optimizing energy consumption. During grain drying, it is essential to control the exposure time, the heating temperature of the grain (or seeds) and the drying agent, and the amount of moisture removed in a single pass.

Different types of dryers require varying exposure times, ranging from a few seconds to several hours. Since 1997, grain drying protocols for the shaft-type (single-pass and recirculation) equipment then in use in Ukraine were governed by the "Instructions on Drying Food and Feed Grain and Oilseeds and on the Operation of Grain Dryers" (*Odessa-Kyiv, 1997, 72 pp.*). However, the country's inventory of such machinery subsequently expanded rapidly to include dryers from various foreign manufacturers. They had different productivity, different designs, and new types emerged – modular column and tower models, which implemented drying methods and modes different from those used in shafts. Moreover, each manufacturer recommended specific grain drying protocols tailored to its own equipment.

Therefore, given the wide variety of available drying methods and modes, grain drying equipment specialists must have an understanding of how the modes used during drying can affect the quality of dried grain, and understand what happens in grain as a living organism when it is dried under various conditions.

One of the most critical operational parameters in the grain drying process is the maximum grain heating temperature; the quality of the dried grain depends on adhering to this limit. Specifications for all drying units list empirically determined temperature limits based on initial moisture content and the intended use of the grain (food, feed, or seed). Seed grain has the lowest maximum heating temperatures, while feed grain has the highest. These values also depend on the uniformity of the drying process. For instance, in recirculating grain dryers equipped with pre-heating chambers where grain moves in a falling layer, the maximum heating temperatures are 5°C higher than those for louvered-type dryers, as the falling-layer design ensures more uniform heating. This prevents the grain from overheating during drying. It should be noted that drying uniformity and heating efficiency decrease as the grain layer thickness increases. Consequently, shaft-type grain dryers may allow for higher maximum grain heating temperatures compared to, for example, column-type dryers.

The maximum heating temperature for grain during dehydration is primarily determined by the biochemical changes occurring within the protein complex of the germ and endosperm (*Kirpa, 2017*). These changes are characterized by the extent of protein denaturation, which depends on several factors: grain temperature, moisture content, duration of heating, and protein properties.

The science of drying is typically divided into three interconnected sub-disciplines:

- drying theory – examines the general analytical and experimental principles of the process, heat and moisture transfer mechanisms, and kinetic and dynamic models.

- drying technology – focuses on the properties of materials undergoing drying (e.g., various types of grain) and the selection of drying regimes, modes, and methods for each specific type.

- drying engineering – covers the practical implementation of drying in various types of drying systems, as well as equipment design, calculations, and operation.

These three components work in synergy: theory provides formulas and understanding, technology offers specific operating parameters, and technique supplies the tools for implementation.

In general, distinct historical stages in the development of drying theory, technology, and equipment can be identified. The first stage concerns the fundamentals of the fluid dynamics and thermodynamics of moist gases. The turn of the 20th century saw the emergence of fundamental theories regarding gas flow, heat transfer, and mass transfer in moist gases. For instance, between 1900 and 1911, V.E. Grum-Grzhimailo developed a theory of gas flow in furnaces and drying units, based on classical laws of gas dynamics. His monograph *Flame Furnaces* (1924) included sections on drying units utilizing natural gas circulation.

In 1918, L.K. Ramzin presented the fundamentals of moist-gas thermodynamics and introduced a graphical-analytical method for dryer calculations utilizing the Id diagram. Similar I-d diagrams were published by Mollier in 1923. Hirsch, Hausbrand, and other scientists also contributed to this field.

Another stage involved the kinetics and dynamics of drying. In 1904, P.S. Kosovich made a significant advance in understanding the drying patterns of moist soils by identifying two distinct drying periods: the first (intensive) and the second (internal). Later researchers (*Lewis, Sherwood, Filonenko, Posnov, Fedorov, Minionovich*) expanded upon these ideas by mathematically analyzing moisture transport via both molecular and macroscopic mechanisms. The moisture conductivity coefficient emerged as a key process parameter, proving to be dependent on the grain's moisture content and temperature.

Academician M.I. Lykov and his research school made a particularly significant contribution. In 1932, Lykov established the basic principles of drying and proposed the concept of an "evaporation zone," where the surface layer is not the only source of moisture – some of the evaporation occurs deep within the material. In 1934, he discovered the phenomenon of thermal-moisture conductivity – the movement of moisture under the influence of a temperature gradient, similar to thermal diffusion in gases/liquids. His 1938 monograph, *Kinetics and Dynamics of Drying and Moistening Processes*, presented these fundamental theories. Concurrently, Filonenko developed other aspects of drying kinetics in his monograph *Kinetics of the Drying Process* (1939). Thus, this stage of drying was analyzed for the first time as a process of unsteady-state heat and moisture transfer, underpinned by precise mathematical models.

The third stage involved the development of drying technology. Once the theoretical foundations had been established, work began on the technology itself – specifically, the development of applied methods, the selection of operating parameters, and the determination of process execution. Academic schools led by Rebinder, Lipatov, Dumansky, and Kavkazov laid the groundwork, particularly regarding the nature of the bond between moisture and the material. Rebinder formulated the concept of various forms of hygroscopic moisture and their energetic bonding with the material – a concept that serves as the basis for selecting drying parameters. Furthermore, biochemical studies of grain conducted during this period (by Academicians Oparin, Kretovich, Kazakov, Kozmina, Trisvyatsky, Lyubarsky, and others) demonstrated how temperature, drying conditions, and moisture-retention mechanisms influence enzymatic processes as well as the protein and starch composition of the grain.

The fourth stage involves a comprehensive approach, non-equilibrium processes, and new driving forces. In the later period (the second half of the 20th century and the 21st century), the drying process began to be viewed as a combination of energy and mass transfer, taking into account transient and non-stationary effects. Mass transfer potentials were employed within the framework of the theory of irreversible processes.

The discovery of molar moisture transfer under the influence of unrelaxed pressure (internal gradient) (works by Lebedev, Maksimov) gave impetus to taking into account convective diffusion in drying models.

Modern research incorporates coupled effects – such as diffusion-thermodiffusion models and the consideration of total pressure, temperature, and non-uniform fields. Some authors are also experimenting with the influence of electric and magnetic fields on moisture transport, opening up new prospects in drying technology.

Thus, the development of drying theory and technology has evolved from the classical laws governing gaseous media to sophisticated models of nonlinear mass and heat transfer in multiphase materials.

Forms of moisture binding in grain

One of the key aspects of drying technology is understanding the nature of the bond between moisture and the grain material. Based on the binding energy of moisture within the solid phase, Academician Rebinder classified all forms of moisture into three categories:

- ionic (chemically bound) moisture – this moisture is so tightly bound to the material that it can be removed only by breaking chemical bonds or through thermal degradation (calcination). In the context of grain drying, it is often disregarded and considered part of the dry matter.
- molecular moisture – bound to the material via molecular adsorption or weak interactions such as hydrogen bonding. It is removed upon heating but requires energy.
- physicochemical-bound (more loosely bound) moisture – contained within the capillaries and pores of the grain. It is less strongly bound than molecular moisture, yet its removal still requires additional energy..

In addition, the grain contains moisture in macro- and microcapillaries - water that fills the pores, channels, pathways and its connection is much freer. This is the moisture that leaves the grain first during drying. Such a classification makes it possible to predict the removal kinetics: pore moisture is removed first, followed by molecular moisture, while ionic moisture either remains or alters the grain's structure. Understanding these binding states is key to selecting the optimal drying regime and avoiding grain damage or excessive energy consumption.

Grain kernels are hygroscopic objects: they are capable of absorbing water vapor from the air (sorption) or releasing it (desorption). The amount of moisture absorbed depends on temperature, relative humidity, the type of grain crop, and the initial moisture content.

The state in which grain is in equilibrium with the surrounding air (with both the grain moisture and the air conditions remaining stable) is known as equilibrium moisture content (Wp). Each grain crop has its own specific Wp value for any given temperature and air humidity.

When the temperature drops or air humidity rises, grain absorbs moisture; conversely, as the temperature rises or air humidity decreases, moisture evaporates from the grain. It is precisely this property that is taken into account when ventilating and aerating the grain.

Air or a mixture of air and combustion gases is typically used for grain drying. These gases serve as the drying medium: they transfer heat to the grain and carry away water vapor. Moist air is a mixture of dry air and water vapor. In general, a grain dryer deals not with dry air but with a moist mixture, sometimes combined with fuel combustion products. The key parameters characterizing the state of moist air are: total pressure, partial pressure of water vapor, relative humidity, moisture content, specific weight, volume, temperature, and enthalpy.

The amount of water vapor in the air depends on temperature and pressure. If the air contains the maximum amount of vapor possible at a given temperature, it is called saturated; otherwise, it is unsaturated.

When designing grain dryers and selecting parameters such as temperature, air velocity, and energy recovery methods, it is essential to carefully consider these factors, as they determine the efficiency of the drying process and the extent of associated losses.

Before carrying out the drying process, it is necessary to select the operating parameters: temperature, airflow rate, grain bed depth, residence time, and the temperature profile (gradual or rapid). An optimal regime is one that minimizes quality loss and damage while maximizing energy efficiency.

Typically, the process takes place in two stages (*Popovych, 2024*):

- intensive drying mode – high temperature, high driving force (i.e., a large moisture and temperature gradient). In this mode, evaporation occurs primarily at the surface;
- diffusion drying mode – when surface evaporation slows down, airflow is maintained but intensity is reduced, and the dominant process becomes the internal diffusion of moisture from the inner layers of the grain.

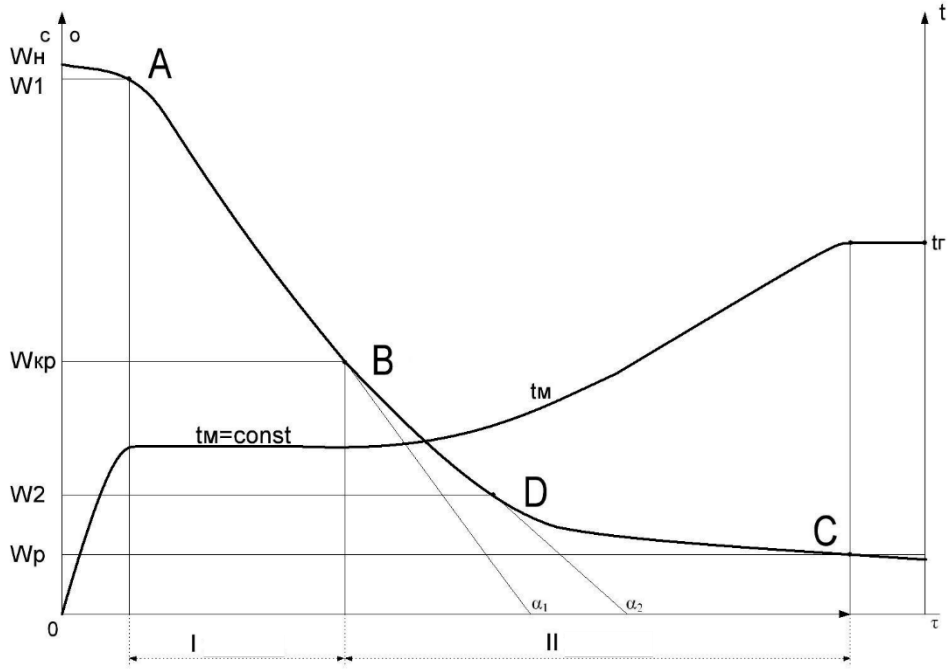

Fig. 3 – Three periods on the drying curve:
OA – period of heating the material to the wet-bulb temperature;
AB – constant drying rate period (I);
BC – falling drying rate period (II).

It is essential to avoid thermal and mechanical damage to the grain (such as scabs or cracks), scorching, and the denaturation of proteins or carbohydrates. Temperature profiling is often used in the technology: for example, initial heating to an average temperature, then stabilization or temperature reduction in the final stages.

After the main drying stage, aeration or passive ventilation is often employed to distribute moisture evenly and cool the grain. This is particularly important if the grain initially had uneven moisture levels.

Grain drying is an energy-intensive operation. The cost of fuel or electricity (depending on the type of dryer) is the dominant component of the drying tariff. For instance, if drying corn requires removing 10% moisture, gas costs account for 50–60% of the total drying tariff.

To reduce costs, practices such as heat recovery, the use of warm exhaust gas mixtures, integration with other energy systems (biogas, heat pumps), and the optimization of operating modes are employed.

Grain drying systems can be classified based on air supply methods, design features, scale, heat sources, etc. By air flow direction:

- concurrent-flow (air moves from bottom to top through the grain layer)
- counter-flow (air moves from top to bottom)
- cross-flow (combination of lateral and vertical movement)

By type of drying unit:

- tubular dryers, where grain moves along a tube and air moves transversely or longitudinally
- column dryers (vertical towers)
- drum dryers
- plate dryers
- thin-layer dryers (thin layer of grain)
- rotary and loop dryers

Each design has its own advantages: for instance, shaft and tower types allow for higher loads but require careful airflow design, whereas drum types are compact but offer less effective humidity control.

The sources of heat are:

- direct heating – combustion of fuel (gas, fuel oil, wood) directly within the drying air;

- heat transfer fluid heaters / heat exchangers – air heating via a heat transfer medium (steam, hot water);
- electric heating;
- solar energy – air preheating using solar collectors;
- heat pumps / heat recovery – heat recovery from exhaust or other streams..

Modern systems employ combinations of these methods to increase efficiency.

Heat recovery (utilizing heat from exhaust gases) is a key factor in reducing energy consumption. Technologies in this area employ heat exchangers, recovery units, intermediate heaters, ventilation systems with heat recovery, and air supply controls.

Modern grain dryers are equipped with sensors for temperature, humidity, pressure, and air velocity, as well as controllable drives for fans and valves, and control and monitoring systems. This enables real-time adjustment of the operating mode in response to changing conditions (such as ambient temperature, humidity, and fluctuations in grain moisture content).

Overall, several ways to improve drying efficiency can be identified (*Stankevich, 2015*). With technological advancements and rising energy costs, the search for new methods is becoming increasingly relevant:

- - non-uniform fields – acoustic, electric, or magnetic. For example, the application of an acoustic field or electric/magnetic pulses can alter the grain structure and weaken moisture bonding, thereby accelerating moisture migration;
- oscillating modes – such as alternating heating and cooling, or heating followed by a "resting" period (pause) - help relieve internal gradient stresses and ensure more uniform grain drying;
- vibration drying, where vibration alters capillary moisture content and facilitates improved water outflow; - infrared irradiation, using intermittent exposure to stimulate internal moisture movement without overheating the surface layer;
- hybrid approaches (IR + convection, acoustics + hot air) that can yield a synergistic effect;
- optimization of aerodynamics and airflow through modeling to precisely design air ducts, eliminate "dead zones," and ensure uniform air distribution;
- energy management through the implementation of heat recovery systems, heat exchangers, multi-stage configurations, and hybrid energy sources (biomass, solar), as well as integration with other processes (drying other materials, warehouse ventilation).

The evolution of heat and mass transfer theory – moving from classical gas-dynamic foundations to modern models that account for non-steady-state conditions, convective diffusion, and coupled heat and moisture transport – has laid the groundwork for new approaches. Consequently, drying technologies and equipment have kept pace with these theoretical advances, evolving through innovations such as acoustic, electric, and pulsed operating modes, automation, and hybrid energy systems.

The way to improve drying efficiency in the future is through:

- active implementation of hybrid methods (IR, acoustic, pulsed modes);
- use of automatic control systems;
- development of energy-saving schemes (heat recovery, heat exchangers, alternative energy sources);
- precise calculation and mathematical modeling in dryer design;
- improvement of dryer designs featuring uniform airflow, minimal dead zones, and adaptive configurations..

CONCLUSIONS

The study systematizes the key stages in the development of the theory, technology, and technical equipment for drying agricultural materials. It establishes that the evolution of drying as a technological process progressed from the use of natural factors – such as solar energy and atmospheric air – to the application of controlled thermal processes and specialized drying systems. The continued development of agricultural production drove the transition from empirical drying methods to scientifically grounded technologies based on the principles of heat and mass transfer.

It is shown that the scientific theory of drying was developed based on fundamental principles of thermodynamics, heat transfer, diffusion, and hydrodynamics. Key outcomes of this process included the formulation of concepts regarding drying kinetics, moisture transport mechanisms, drying periods, critical and

equilibrium moisture content, and thermo-moisture conductivity. This established a theoretical foundation for the design of drying equipment and the determination of optimal operating conditions.

It has been established that the development of drying technology is directly linked to the need to account for the physicochemical, thermophysical, and biological properties of agricultural materials. For grain, limiting heating temperatures is of particular importance, as excessive heat exposure can lead to a deterioration in processing properties, protein denaturation, and a reduction in sowing quality. Therefore, an optimal drying regime must ensure the simultaneous achievement of the required final moisture content, the preservation of product quality, and the minimization of energy consumption.

The evolution of dryer designs has been analyzed, with shaft, rotary drum, column, hopper, recirculation, and conveyor types – among others – gaining widespread use. Their development has focused on increasing throughput, drying uniformity, and process controllability, while reducing specific energy consumption. At the same time, the diversity of designs and process configurations necessitates a differentiated approach to selecting drying parameters based on the material type and initial moisture content, the intended application, and the specific design features of the drying unit.

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