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DRYING TECHNOLOGIES IN FOOD ENGINEERING

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INVITED PLENARY LECTURE

Abstract: *Drying is one of the primary methods of food preservation in the agro-industry and is a complex and energy-intensive process. In recent years, research in the fields of natural and technical sciences has focused on optimising the energy requirements of industrial systems to sustainably develop and modernise various technologies. Many researchers deal with drying in the agro-industry, as evidenced by an enviable number of publications on this topic. In recent years, a large number of conferences and round tables on the implementation of energy-efficient technologies have been held in the Republic of Serbia. Conclusions have been adopted that the Republic of Serbia, except for the Law on Energy, has no accompanying regulations that would regulate designing and constructing of centres for drying, storage and processing of agricultural products. Drying is one of the basic technological operations in the food processing industry. Attention was drawn to the extremely high energy consumption of drying plants. Some of the proposed solutions are rationalising energy consumption at existing plants and adopting new, more economical plants based on new technologies. This paper reviews the available literature and research of a large number of international authors dealing with advanced drying technologies, improving the energy efficiency of drying systems and environmental aspects of drying to ensure sustainable development, with a tendency to provide a comprehensive insight into the complexity of the drying process, trends in the development of equipment and technologies, as well as ways to properly select the appropriate technologies depending on the specific feedstock being dried.*

Key words: *Drying, dryer classification, modern technologies, energy efficiency, ecology.*

1. INTRODUCTION

In the recent history of mankind, especially in the last hundred years, the changes in the biosphere have not been unnoticed and negligible, but, on the contrary, alarming. The constant development of science and technology, coupled with the dynamic way of life in modern society, has brought natural resources to critical limits, disturbing their global ecological balance. The demands of modern society have been and they continue to be supported by the existing stocks of fossil fuels on earth. However, those stocks are limited, and their complete depletion is inevitable. Research in the fields of natural and technical sciences in recent years has focused on solving this problem. Solutions are being sought to restore harmony and ecological balance in modern society without drastic effects on the quality of life and significant sociological changes.

Drying, as one of the most important methods of food preservation in the agro-industry, significantly affects the environment in ecological terms. A partial or complete separation of water from biological materials is a complex process that consumes a large amount of energy. Influential factors such as the time interval of the drying process, product quality, thermal sensitivity of the biological material to be dried and the like determine the drying regimes that are often a compromise between these factors. The adoption and widespread use of eco-friendly drying technologies are slow due to several factors, and short-term cost-effectiveness and current profitability are often the main reasons. Research in the field of drying must focus on solving these problems and demonstrate the possibilities of applying alternative technologies to educate manufacturers and users of drying systems.

This paper reviews the literature and research to promote modern drying technologies that are often obtained by a combination of existing technologies. The use of new technologies promises economic and environmental benefits, and a large number of researches deal with their application in drying systems. However, their mass use in the Republic of Serbia on farms and in the industry has not yet occurred despite efforts and promotion.

Accordingly, this lecture is designed to cover, combine and analyse all relevant categories important to describe the technology of drying food products, namely: basic principles and theory of drying, variety of equipment and drying systems, selection of appropriate drying technologies, the way of proper selection of drying systems, combined drying technologies, dried product quality, the energy efficiency of the drying process and ecological aspects of drying.

2. BASICS OF DRYING AND DRYING EQUIPMENT

Many authors have written about the theory and basic principles of drying in various books 1-7.. In addition to learning about physico-chemical concepts related to food dehydration and psychrometry, various commercial drying systems can be classified into four generations 7.:

1) dryers for drying solid feedstocks,
2) pulp and slurry dryers,
3) sublimation dryers and systems for osmotic dehydration,
4) dryers that apply specific drying techniques.

In addition to thorough theoretical analyses and discussions on the methods of classification, selection and design of dryers 6., the wider professional literature also discusses various aspects of experimental work related to drying. Thus, for example, it is pointed out that the general objectives of drying experiments 8. are: selecting appropriate drying equipment, establishing set requirements, testing the efficiency and capacity of the existing drying equipment, testing drying effects on the final product, and analysis of drying mechanism. Various experimental techniques have been carried out to determine the appropriate drying parameters, such as determining the optimal moisture content, establishing characteristic equilibrium states in the sorption and desorption processes, determining thermal conductivity, effective diffusivity, etc. In the food processing industry, research focuses on important factors such as food drying goals, determining residual moisture content for prolonged storage, monitoring certain food properties, optimising appropriate drying techniques, researching varieties suitable for dryers and researching to minimise negative changes of dried product quality 6..

The drying equipment and systems used in the agro-industry vary depending on feedstock. Different types of drying equipment are used for drying agricultural products 6., starting from complex grain drying systems, all the way to different principles of operations of fruit and vegetable dryers. Researching and collecting the necessary information for selecting and designing of drying systems are a complex and important work 9.. This is confirmed by data collected by reviewing commercial drying practices in parts of Europe, Africa and Asia, and analysing different types of dryers, factors influencing selection, drying different types of fruits and vegetables, preparation processes, quality control and dehydration economics 10..

3. CLASSIFICATION OF DRYERS

In modern industrial production, it can be stated with certainty that there is no product whose basic feedstock at some stage has not gone through some drying processes. The costs of energy transport in larger systems are not negligible and directly depend on the moisture content in the material to be dried, so it is desirable to implement different ways of saving energy 11.. In a mass-production system, even minimal savings at the local level can accumulate significant resources in the long run. The choice of adequate drying technology in certain branches of industry, such as the agro-industry, is very delicate and sensitive, especially in terms of preserving product quality. Going beyond the precisely prescribed time-temperature coordinates in the drying process can cause degradation of the quality of the dried product, which can be somewhat eliminated in recirculation types of dryers. Also, the food industry requires the application of continuous drying technologies.

A large number of studies are conducted to determine exactly what and how to dry 6.. Table 1 presents the possibility of using certain types of dryers depending on the mechanical characteristics and shape of the feedstock to be dried. In contrast, Table 2 shows and classifies the possibilities of using certain types of dryers depending on the total retention time of the feedstock in the drying process. The ways of classifying the types of dryers that can be found in the literature vary from author to author.

Table 1. Dryer selection versus feedstock form 6.

Nature of feed	Liquids			Cakes		Free-flowing solids					Solids
	Solutions	Slurries	Pastes	Centrifuge	Filter	Powder	Granules	Fragile crystals	Pellet	Fibers	
Convection dryers											
belt conveyer dryer							●	●	●	●	●
flash dryer				●	●	●	●			●	
fluid bed dryer	●	●		●	●	●	●		●		
rotary dryer				●	●	●	●		●	●	
spray dryer	●	●	●								
tray dryer (batch)				●	●	●	●	●	●	●	●
tray dryer (continous)				●	●	●	●	●	●	●	
Conductive dryers											
drum dryer	●	●	●								
steam jacket rotary dryer				●	●	●	●		●	●	
steam tube rotary dryer				●	●	●	●		●	●	
tray dryer (batch)				●	●	●	●	●	●	●	●
tray dryer (continous)				●	●	●	●	●	●	●	

However, three common principles can be noticed – the principles on which these classifications are based 2, 12., and they are:

1) the method of supplying heat to the material to be dried,

2) drying mode in terms of selected drying temperature (high or low) and drying pressure parameters (vacuum or atmospheric), and

3) how the material is treated in the dryer.

In accordance with these principles, it is possible to deepen the analysis, however, the further introduction of subclassifications has no practical significance, so it is sufficient to remain at the level of analysis of the above three principles.

Heat supply to the material to be dried is possible by any heat transfer mechanisms: convection, conduction or radiation. Convection is one of the most common ways, using atmospheric air (most often), inert gas (nitrogen, etc.), direct combustion products or superheated steam as a medium for transporting steam 6.. This drying method is also called direct drying. Conductive indirect drying is suitable for drying of very wet or very thin materials and is often performed using vacuum drying regimes. Indirect drying and direct drying are often applied at the same time. Radiation drying is achieved by emitting electromagnetic waves at different wavelengths, from the visible part of the spectrum to microwaves. This drying method is extremely expensive and is rarely used as the only one, but it is usually combined with convective drying methods.

According to 12., when heating the material during drying, four heating modes prevail: convective (Fig. 1a), conductive (Fig. 1b), radiation (Fig. 1c) and dielectric (Fig. 1d).

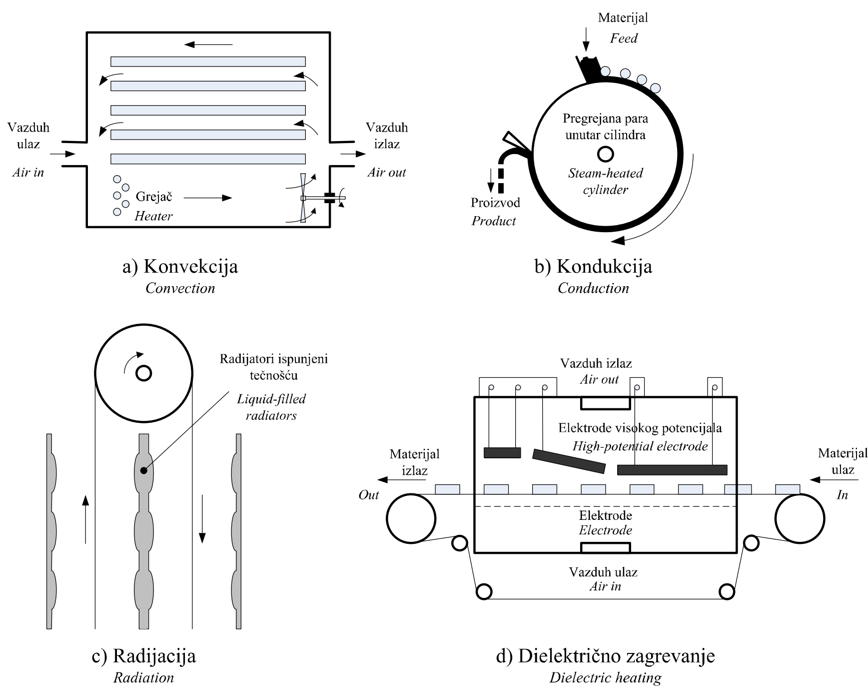

Figure 1. Heating methods in drying 12.

Most dryers work at pressures close to atmospheric, which greatly simplifies the construction of the dryer and the performance of the equipment used. However, in special cases when, for example, the material must be dried without oxygen or at low temperatures, the so-called vacuum drying (at low temperatures – sublimation drying) is used.

The way the material will be treated inside the dryer itself significantly affects the drying costs. Table 2 compares the usual material treatment method, the type of dryer and the type of material encountered in practice today.

Table 2. Capacity and energy consumption for selected dryers 6.

Method	**Typical dryer**	**Typical materials**
Material not conveyed	Tray dryer	Pastes and granules
Material falls by gravity	Rotary dryer	Granules
Material conveyed mechanically	Screw-conveyor, paddle	Wet sludges and pastes
Transported on trucks	Tunnel dryer	Wide range of materials
Sheet-form or roll materials	Cylinder dryers	Paper, textiles, pulp
Conveyed on bands	Band conveyor dryer	Pellets, grains
Material suspended in air	Fluid bed	Granules
Slurries and solutions atomised in air	Spray dryer	Milk, coffee, etc.

4. DRYER SELECTION

For the correct selection of the dryer, it is necessary to determine a few basic facts – pieces of information, which represent the necessary inputs for a correct selection process.

Some of the most important are:

- drying mode, i.e. whether the drying is tray or continuous;
- physical, chemical and biochemical properties of the wet material, as well as the desired properties of the dried material;
- the necessary pre-preparation of the drying material and the necessary procedures to be taken after the completion of the drying process;
- the moisture content of wet and dried material;
- drying kinetics;
- quality parameters;
- consideration of safety aspects of the drying process (fire resistance, explosiveness and toxicity of the process);
- product value;
- level of automatic regulation of the drying process;
- toxicological properties of the product;
- capacity;
- types and prices of fuel, energy resources or electricity;
- environmental impact;
- space for the accommodation of the plant.

In recent years, a large number of studies have emerged **13-16**. focusing on one or more aspects of drying. Modern drying technologies are compared with conventional methods **17**. to find alternative solutions for individual drying problems of certain specific materials **18-20**.. More detailed information about the process of designing dryers is usually an industrial secret. Some researches **21, 22**. are directed towards unification and standardisation of the methodology of production of industrial dryers.

5. OVERVIEW OF DIFFERENT TYPES OF DRYERS

Indirect dryers (contact or conductive) are those dryers in which the heating medium is not in direct contact with the material to be dried, but indirectly, via a heated surface **23**.. The drying temperature for these types of dryers ranges from -40°C (for sublimation drying) to 300°C (for dryers that are heated directly by combustion products). There are four basic types of indirect dryers **24-26**.: tray dryer with shelves (bars/rungs), indirect-contact rotary dryer, tray rotary vacuum dryer and mixer dryer.

Rotary dryers have a rotating roller with an axis set at a small angle to the horizontal, by which the material is transported, mixed at the same time, and at the same time dried with a suitable agent, directly or indirectly 6, 27.. Fluidised bed dryers are mainly used for drying wet powders and granules, which can be fluidised. For this type of dryer, it is very important to know the hydrodynamic properties of the fluidised bed **28**., to know the minimum flow rates, and timely analysis of the main advantages and disadvantages of using this type of dryer on a specific material **29**..

Roller dryers are used for drying liquid organic and inorganic substances. On the inside of the roller, steam, hot water or oil flows, and on the outside, a thin layer of liquid or paste material is dried. These dryers are often used in the drying of slurries: rice 30., flour 31., etc., or pharmaceutical products **32**..

Material spray dryers have a chamber into which liquid material that is dried in an atomised state is inserted. Spraying is the most important operation in a spray dryer **33**., and the size of the spray drop and the distribution of agents and materials in the dryer need to be optimised **34**..

According to **35**., the sublimation dryer (vacuum) is cost-effective for use only when drying specific materials of organic origin such as blood plasma, hormonal solutions, superconducting materials, surgical material for transplantation, cells infected with bacteria and viruses. There is a justification and advantage of using this drying method in the food industry **36**., regardless of the fact that this technology is dominant in the pharmaceutical industry **37, 38**.. Microwave and dielectric drying first appeared at the beginning of the twentieth century. The use of electromagnetic waves of a certain frequency and wavelength is an efficient way to heat materials in industrial production **39**., and with proper selection and sizing of equipment **40**., the advantages of application in the food industry **41, 42**. are emphasised.

Solar drying is one of the oldest types of drying and technologies for using this type of renewable energy are constantly being improved. A large number of researches on the justification of investing in such installations have been conducted **43, 44**., while many authors deal with drying various materials, primarily food products, such as drying cereals, coffee, grapes, peanuts and fruits and vegetables **45.**, drying of grapes, walnuts, tobacco **46**., etc.

Fluidised bed drying has been used successfully since the 1950s. The geometric, physical and hydrodynamic characteristics of these dryers were addressed by **47, 48**.. Some authors point out the advantages of this type of drying of specific materials such as salt dehydration **49**., drying of pigments **50**. and the like.

Concentrated jet spray drying is used primarily during the continuous drying of the material, which is most often in the form of a roll (production of paper, photographic films, textiles, carpets, etc.). A large number of authors are engaged in research of heat and mass transfer in this type of drying: studying the shape of the jet **51, 52**., determining the value of Nusselt number **53**., determining the optimal angle at which the jet reaches the material to be dried **54**.. Pneumatic drying is the most commonly used type of continuous convective drying. Simultaneous pneumatic transport of particles and their drying is a complex process. Numerous authors deal with numerical simulations of these processes, namely: determining the optimal size of transported particles **55, 56**., software shaping and modelling 5., as well as experimental and numerical analyses of heat transfer processes and drying kinetics 57.. Conveyor drying is a type of drying that can be used with a large number of materials. The material is transported on a conveyor belt and at the same time blown with hot air **6**.. Infrared drying is the most commonly used type of drying in the industry and at the same time the type of drying that requires the largest amount of energy. According to research **58**., Russia is a country where there are most such dryers, followed by the United States and Eastern European countries. Theoretical research and experimental work on the use of these dryers were conducted in the paper, cardboard, textile and paint industries **59, 60**., while the research **61**. pointed out the advantages and disadvantages of the use for food drying in the food industry.

Superheated steam drying is one of the oldest drying concepts and it appeared in the nineteenth century at the time of the steam engine and the industrial revolution **19**.. Special advanced drying technologies are developed due to the requirements for high product quality, increased productivity, easier control, energy efficiency of drying plants, reduction of a negative impact on the natural environment. The main trends in the introduction of advanced technologies are **62**.:

- the use of superheated steam in direct drying,
- the use of indirect conductive heating,
- the application of combined heat transfer methods,
- the application of volumetric heating using microwaves and radio waves,
- the use of two-stage dryers,
- the use of special combustion technologies,
- the design of flexible multiprocess dryers.

6. COMBINED DRYING TECHNOLOGIES

At the end of the twentieth century, various drying methods were designed to obtain top quality products, in which energy consumption was reduced to a minimum due to various improvements in the process of mass and energy transfer.

In combined drying processes where two phases dominate 63.: 1. the phase of freezing, 2. the phase of contact (conductive) drying in vacuum, a very good looking product is obtained and its rehydration capacity is comparable to the capacities of sublimation of dried material. Also, with the technology that combines simultaneous osmotic and convective drying of grapes, which is achieved in a fluidised bed of sugar and semolina, with pre-treatment immersion in ethyl oleate, the duration of the drying process has been halved **64, 65**.. The use of microwaves for heating materials in drying systems has become popular in recent years. The possibility of selective microwave heating in combination with pneumatic transport of the material to be dried, using forced air flow, is used for different types of products, for example: drying thin-layered carrots **66**. or drying sliced potatoes **67**.. The quality of microwave-dried products improves when combined with osmotic drying **68**.. Also, some research shows that the combination of microwave drying and vacuum drying gives good results when drying fruit **69**., cranberries **70, 71**. and peas **72**..

7. QUALITY OF DRIED PRODUCT

According to some research, despite the fact that they are considered lower quality products among processed foods, dried food products are gaining popularity **65**.. This is confirmed by the constant growth of the dried food market. Analysing the mutual influence of drying on the quality of the final product 73., the concept of quality is quite complex in the food industry sector. By optimising the process of drying food products **74**., it is noticed that the concept of the quality of the dried products is often different for the consumer and for the industry.

The quality of the final product is often associated with those characteristics that are acceptable to consumers. Thus, for example, rehydration is the most researched quality parameter, in addition to colour and shrinkage **75**.. Numerous authors **75-80**. consider the kinetics of drying of individual foods determine various factors that affect the change in the quality and control the parameters to achieve the desired quality of the final product, for example: a colour change parameter as one of the important quality factors **75**., shrinkage (contractions) of products during drying **81-83**. or changes in the texture and physical structure of the dried material and determines their influence on reconstruction and rehydration, as well as on organoleptic characteristics such as mouthfeel **84**.. In research 85. that deals with drying fruits and vegetables, fruits and vegetables are subjected to various sub-treatments (immersion in alkaline solutions, bleaching, etc.) to improve and maintain their characteristics during drying. Sulfur dioxide treatment is used to preserve the colour of the dried product. Sulfur dioxide and sulfites act as inhibitors of enzyme activity and prevent discolouration. The relationship between drying parameters and product quality change can be described by special methods **86, 87**..

Properties that significantly affect quality can be classified into several groups **86**.:

1) Structural properties (*density, porosity, pore size, specific volume, ...*)
2) Optical properties (*colour, appearance, ...*)
3) Mechanical properties (*resistance to pressure and tension*, ...)

4) Thermal properties (*glassy, crystalline or rubber state of the product*, ...)
5) Sensory properties (*smell, taste, aroma, ...*)
6) Nutritional properties (*vitamins, proteins, ...*)
7) Rehydration properties (*degree of rehydration, rehydration capacity*, ...)

Quality characteristics are influenced by many factors that occur during drying, but all of them are ultimately related to the drying temperature and the dynamics of moisture removal from the material. The unique conclusion derived from the publications of the aforementioned authors is that the heat input and the exposure time of the product to elevated temperature and hot air during drying affect the nutritional quality of food products. It shows large chemical changes that occur during drying, such as browning, lipid oxidation and loss of original natural colours. In addition, the drying process affects rehydration, solubility, texture appearance and loss of aroma. Elevated drying temperatures and periods of exposure of the material affect its nutritional value, vitamin and protein contents, as well as the microbiological structure of the material. It has been shown that there is a noticeable loss of vitamin C and vitamin A during drying. Also, the loss of natural pigments such as carotenoids, chlorophyll and xanthophyll is associated with the discolouration of dried fruits and vegetables. Although the change in colour is sometimes associated with unwanted chemical changes that occur in the material, the real problem is in (non)acceptance by consumers. Preservation of these pigments during dehydration is very important mainly to make the product attractive and acceptable to consumers.

8. THE EFFICIENCY OF THE DRYING PROCESS

Exergy is work that is available in gaseous, liquid and solid materials as a result of its unbalanced state in relation to a reference state. The farther the system is from equilibrium, the more work can be obtained from it. The concept of exergy derives from the Second Law of Thermodynamics, and its meaning has been discussed by various authors **88-101**.. A common approach in exergetic analysis found in the literature is to identify all elements that contribute to the increase of available work in the analysed system. In contrast, exergy losses in the system are generated through the irreversibility of appropriate processes caused by imperfect performances in real conditions **97**.. By exergetic analysis, we can compare real performances in relation to those in which there is no or little necessary process driving force, i.e. that exergetic loss is higher when the process driving force is also higher **102-104**.. Theoretically, the only unavoidable loss in a heat pump dryer is that which occurs due to humidification of the air in the dryer chamber **105**.. This is in stark contrast to conventional dryers, where the heating of the process itself represents a loss. Exergetic analysis of heat pump drying can be performed at the level of physical and chemical processes in the system **106**.. In such analyses, the term "exergetic mixing change" is often used for the adiabatic process of air saturation in the drying chamber. Exergetic analysis of the drying process is desirable when considering drying at higher temperatures **107**..

9. ECOLOGICAL ASPECTS OF DRYING

In industrialised countries, where environmental awareness is at a higher level, special protocols regulate the production and application of appropriate drying technology, taking into account various influencing factors in the early stages of designing a drying installation. Thus, for example, the United States Environmental Protection Agency requires that special attention be given to when designing a drying system:

1) characteristics of the material to be dried,
2) the control of dust and particle production during drying,
3) the storage of dried products,
4) the control of humidity and temperature in the material to prevent bacteriological malfunctions,
5) the position of the drying system in relation to the sewage systems,
6) capacities of the system and infrastructure to which it is connected,
7) the collection and storage of waste material,
8) the energy efficiency of the plant,
9) safety risks and safety at work.

However, very few scientists and researchers, who carry out research in the field of drying, try to see the concept of drying in a global context of the mutual intensive interaction of this process and the environment. The application of environmentally friendly technologies in energy engineering, especially in the field of drying, can reduce irreversibility and increase entropy. There are few authors who look at the energy, exergetic and environmental aspects of the drying process from a global industrial perspective **98**.. The use of biogas, natural gas, waste gas in turbines and heat of solid combustion products in direct drying, as well as superheated steam and hot water waste in indirect drying, are increasingly the subject of research **108**.. Also, in recent times, the production and use of various biomass pellets and their use in drying systems as an energy source have been considered **109**..

10. CONCLUSION

Conducted research in the field of food drying, thorough theoretical analysis and discussion of ways to classify, select and design dryers indicate that drying and selection of drying equipment are a serious process that requires an even more serious approach. The selection of the dryer is influenced by numerous parameters. The justification of neglecting certain parameters may exist, but it is most often conditioned by external influences such as market and consumer requirements, availability of energy sources, accommodation capacities of drying equipment and the like. Most dryers can be used for drying a variety of materials, regardless of certain specifics, of course, within the limits of their design characteristics, so choosing the right dryer for a particular material is a very complex and delicate job. Most publications related to drying have one common conclusion – drying is one of the most energy-intensive operations in the process industry. In the absence of a universal framework for determining drying efficiency, exergetic analysis seems to be a suitable technique. However, exergetic analysis only indicates the potential or possibilities of improving the work process, but it cannot indicate whether it is possible to achieve improvement or how economically rational it would be. Consumers make the final judgment on the quality of the final product in the form of demand, which encourages competition among producers, who are thus forced to take care of more economical business and production on the one hand, and to ensure quality, on the other hand, with appropriate feedstock quality and adequate processing equipment.

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