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EXPERIMENTAL INVESTIGATION OF HEAT AND MASS TRANSFER DURING THE DRYING OF AGRICULTURAL PRODUCTS IN A ROTARY DRUM DRYER

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Abstract The present study focuses on the heat and mass transfer performance of an agricultural-product drying system based on a rotary drum dryer. The main objective is to improve the understanding of heat and mass transfer regularities and increase the stability and overall efficiency of the drying process. Particular attention is given to the influence of drying-air temperature, air velocity, drum rotation speed, and product moisture content on the drying performance of the system. The experimental subsystem provides real measured data on temperature and humidity distribution inside the drying chamber, heat transfer coefficients, and moisture diffusion throughout the drying volume. The mathematical model is intended to predict the thermal and moisture conditions of the material during different stages of drying. The analysis demonstrates that uniform thermal conditions and controlled air circulation are important factors affecting moisture removal rate and drying duration. The proposed methodology can therefore contribute to improving the energy efficiency, process control, and product quality of agricultural-product drying systems.

Keywords: heat and mass transfer; rotary drum dryer; modeling; agricultural products; drying kinetics; moisture diffusion; air velocity; drying efficiency.

INTRODUCTION

Agricultural products constitute an important component of global food production and consumption. Nevertheless, considerable quantities of agricultural products are lost after harvesting as a result of their high moisture content, inadequate storage conditions, and insufficient preservation technologies [1–3]. Moisture reduction through controlled drying is therefore one of the most important methods for extending the storage life of agricultural products while maintaining their technological and nutritional properties [4]. The drying process represents a complex interaction of heat and mass transfer between the product and the drying medium. Conventional drying technologies commonly require significant amounts of electrical or fossil-fuel energy, which increases operating costs, while the mechanisms governing heat and mass transfer within the drying chamber remain insufficiently investigated under varying operational conditions [5–7].

However, non-uniform airflow distribution and temperature gradients within the drying chamber remain a major limitation of many conventional dryers. Variations in air velocity and temperature across the drying volume can cause uneven moisture removal and increase overall drying duration [8]. Rotary drum dryers can reduce this limitation by providing continuous mixing and more uniform exposure of the material to the drying air [1,3]. Modern drying systems also require detailed information on internal airflow patterns, temperature distribution, and moisture diffusion, which are difficult to obtain through experimental measurement alone. Combined experimental approaches are particularly valuable because they allow simultaneous validation of measured data and simulated heat and mass transfer behavior [9,10].

The combined interaction of drum rotation, airflow distribution, drying-air temperature, and moisture transfer mechanisms within the drum therefore requires further investigation. Accordingly,

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the objective of the present study is to investigate the heat and mass transfer regularities of an agricultural-product drying process using both experimental methods. Particular attention is paid to drying-air temperature, airflow velocity, drum rotation speed, product moisture content, and the overall efficiency of the heat and mass transfer process.

MATERIALS AND METHODS

This study investigates the processing technology for the convective drying of agricultural products using a rotary drum dryer, conducted as part of an experimental.

The technology includes material feeding, dehydration to a specified target moisture content, and subsequent handling of the dried product. Among these operations, dehydration with quality and nutrient retention presents the greatest difficulty. To dry agricultural products with a high initial moisture content, a convective drum dryer was developed. To reduce the cost of studying the drying process, a physical model of the drum dryer was developed for laboratory investigations (Figure 1). The operating principle of the designed dryer is as follows: a drum (1) is rotated on support rollers (2) by an electric motor (4) via a belt transmission (3). The drum rotation frequency is regulated using a frequency converter (5) according to the experimental plan. The wet material is loaded through the throat (6), while the drying agent (air) is supplied from an electric dryer (7) at the required flow rate and temperature. The material mass, fed through the loading throat by the airflow from the electric blower dryer, enters the rotating drum. The drum is positioned at a certain angle θ to the horizontal. As the drum rotates, the loaded mass of material rises to a certain height, and upon separation from the drum wall, the particles fall onto the base with a displacement corresponding to the drum's inclination angle. The mixed material is gradually dried and exits through the lower end of the drum. The residence time of the material inside the drum is determined by its rotational speed, inclination angle, and the airflow velocity of the drying agent, which together govern the intensity of heat and mass transfer between the material and the surrounding air. The dried product is then collected at the drum outlet for further processing and quality assessment. During the drying process, temperature and humidity sensors installed along the drum length continuously record the variation of air and material parameters, allowing the drying kinetics to be monitored in real time.

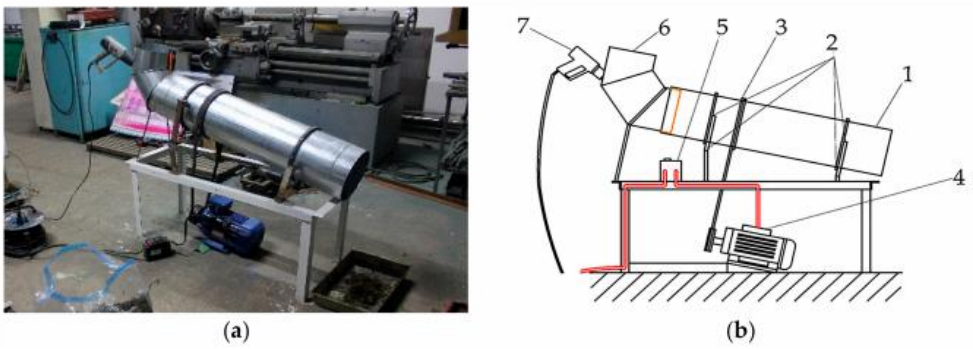


Figure 1. Overall view (**a**) and design diagram (**b**) of the laboratory drum dryer. 1—drum; 2—support rollers; 3—belt drive; 4—electric motor; 5—frequency converter; 6—loading hopper; 7—heater for air supply.

Dryer performance and the quality of the dried product are influenced by the drum rotation rate, airflow speed, and the amount of loaded material mass. An air temperature of 60 °C was selected to preserve the technological and nutritional properties of the processed material. The drum dimensions are proportional to the production-scale counterpart: length of the cylindrical part — 1200 mm; diameter of the cylindrical part — 200 mm; inclination angle — up to 15 degrees.

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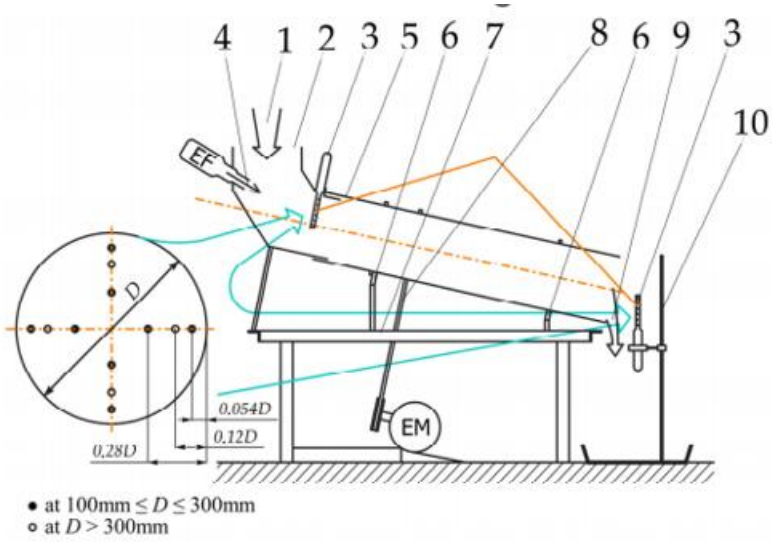


Figure 6. Diagram of the physical model of the laboratory experimental drum dryer. 1—loaded leaf mass; 2—feed hopper; 3—device for measuring air flow velocity and humidity; 4—hot air flow; 5—rotating drum; 6—drum support rollers; 7—dryer frame; 8—drive belt; 9—dried mass; 10—measuring instrument tripod.

The experimental design matrix and its values are shown in Table 3. Each experiment was repeated three times, and the mean values of the response function were determined. The moisture content of the dried material was adopted as the response function. Before each experiment, the air temperature (60 °C) and controlled factors were checked. The moisture content of the loaded and dried material was determined using standard methods [36] with a laboratory drying oven. Temperature, airflow velocity, and humidity were measured using the Testo Smart Device (German company Testo SE & Co. KGaA, Titisee-Neustadt, Germany) [38]. The drum rotation frequency was controlled using a frequency converter (via preliminary calibration). The experimental data obtained were subjected to statistical processing according to the standard method (Machinery for agriculture and forestry. Cylinder driers. Methods of testing), and graphical dependencies on the controlled factors were constructed [39,40]. The moisture of the dried material was determined using the MX-50 Weight Humidity Gauge produced by the Japanese company (A&D Company, Tokyo, Japan, Limited with a 0.02% margin of error) with simultaneous control in the drying cabinet.

CONCLUSION

This study demonstrated that convective drying of processed agricultural material in an inclined rotating drum is an effective method for reducing moisture content by up to 50%. Analytical modeling of material motion within the rotating drum during drying made it possible to develop a comprehensive model linking the transverse kinematics of the particles, the detachment angle, the Froude number, the drum inclination angle, the average longitudinal velocity, and the material residence time. The following relationships were established for transverse motion — Fr(n), θ_tear(n), τ_tear(n) — and for longitudinal motion — $v_z(\beta, n)$, $\tau_c(\beta, n)$.

Numerical modeling of heat and mass transfer for a single particle at different positions relative to the drying-agent flow showed the formation of characteristic moisture gradients over time, which reflect the kinetics of drying. These results made it possible to optimize the residence time of the material in the drying zone.

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Experimental drying in a laboratory-scale drum confirmed the practical applicability of the proposed technology and validated the effectiveness of the selected operating regime under real process conditions.

Correlation-regression analysis demonstrated that the investigated technological factors affect the final moisture content to different degrees. Among the parameters studied, the mass of material in the dryer had the greatest influence, whereas airflow velocity showed a weaker negative effect on the response variable. Considering that $R^2 = 0.50$, the resulting model adequately describes the main patterns and can be used for engineering assessment and rational mode selection, with further improvement of accuracy possible by considering additional factors.

Analysis of the I-d charts made it possible to determine the thermophysical properties of humid air in a simple and visual way, without complicated calculations: at the inlet (T = 63 °C; W = 12.5%); at the outlet from the dryer chamber (T = 43 °C; W = 36%). Accordingly, the air moisture content was d = 0.016 kg/kg and at the outlet d = 0.020 kg/kg. The difference between them amounted to Δd = 0.004 kg/kg, which is related to the drum length and the airflow speed.

Future research should focus on improving energy efficiency through exhaust-air enthalpy recovery and on replacing complex cyclone dryers with drum dryers for the thermal processing of similar agricultural materials. In this context, the use of solar energy to heat the drying agent up to 60 °C is an acceptable energy-saving solution.

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