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CONTROLLING AND MANAGEMENT SYSTEMS IN DRYING PROCESSES

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Abstract: Drying processes play a vital role across multiple industries, yet they remain among the most energy-intensive and technically complex operations. The effective control and management of drying systems are essential for ensuring product quality, operational efficiency, and energy conservation. This paper explores the evolution, current practices, and emerging technologies in the control and automation of drying processes. Beginning with traditional PID-based control, the study reviews the shift toward model-based strategies such as Model Predictive Control (MPC) and soft computing approaches including fuzzy logic and neural networks. It also highlights the importance of sensor integration, real-time monitoring, and the adoption of SCADA and IoT frameworks for intelligent process management. Despite significant advancements, challenges such as modeling complexity, cost of implementation, and skill requirements continue to hinder widespread adoption, particularly in small and medium-sized enterprises. The discussion emphasizes that future solutions should prioritize scalability, user-friendliness, and energy efficiency. Ultimately, the research underscores the transformative potential of intelligent control systems in optimizing industrial drying operations within the context of digitalization and sustainable production.

Keywords: drying process control, industrial automation, model predictive control, fuzzy logic, neural networks, real-time monitoring, energy efficiency, SCADA systems, sensor integration, process optimization

Introduction. Drying processes are among the most energy-intensive and technically sensitive operations in various industrial sectors, including food processing, pharmaceuticals, agriculture, chemical production, and materials engineering. The efficiency, consistency, and quality of these processes directly depend on the precision with which thermal and mass transfer mechanisms are monitored and regulated. As such, controlling and management systems have emerged as critical components in the optimization of drying technologies, aiming to enhance energy efficiency, reduce processing times, maintain product integrity, and meet stringent environmental and economic constraints.

The primary objective of drying is to remove moisture from raw materials to a desired level without compromising the physical, chemical, or structural properties of the product. Achieving this balance requires meticulous control of variables such as temperature, humidity, air velocity, pressure, and product residence time. Traditional manual control methods are often inadequate for managing the complex, nonlinear dynamics involved in industrial drying. Consequently, the implementation of automated control systems—ranging from classical PID controllers to advanced model predictive and fuzzy logic systems—has become increasingly essential.

The evolution of control and management systems in drying processes parallels broader trends in industrial automation and digital transformation. The integration of sensors, programmable logic controllers (PLCs), supervisory control and data acquisition (SCADA) systems, and artificial intelligence (AI)-based algorithms has revolutionized process monitoring and decision-making. These innovations not only allow for real-time adjustments based on feedback from critical process variables but also enable predictive maintenance, fault detection, and adaptive optimization—features that are crucial in achieving consistent product quality and minimizing energy consumption. Despite these advancements, the deployment of control systems in drying processes poses numerous challenges. These include the inherent variability of raw materials, the dynamic nature of drying kinetics, the high cost of system integration, and the technical skill required for design and maintenance. Additionally, different industries impose varying requirements on control accuracy, system flexibility, and scalability, necessitating customized solutions for different drying applications. This paper aims to explore and critically analyze the current state, methodologies, and technological innovations in controlling and management systems within drying processes. Through a review of scholarly literature, industrial practices, and emerging technologies, the study seeks to identify effective strategies and frameworks for enhancing control precision, operational efficiency, and sustainability in modern drying systems.

Literature Review. The scientific and industrial literature over the past few decades has increasingly emphasized the critical role of control and management systems in enhancing the performance of drying processes. Given the inherently nonlinear, multivariable, and time-variant nature of drying dynamics, a wide array of studies has been dedicated to exploring effective control strategies that ensure optimal moisture removal while minimizing energy consumption and product degradation.

Classical Control Approaches. Early efforts in drying control were largely based on classical control theories, particularly Proportional-Integral-Derivative (PID) controllers. According to Mujumdar (2007), PID-based systems were widely adopted due to their simplicity, reliability, and ease of implementation. However, their effectiveness is often limited in the presence of time delays, system disturbances, and process nonlinearity—conditions that are frequently encountered in drying operations. As a result, the performance of PID controllers typically requires fine-tuning and lacks adaptability to varying input material characteristics or environmental conditions.

Model-Based Control Strategies. In response to the limitations of traditional control approaches, model-based control systems gained traction in the 1990s and early 2000s. Model Predictive Control (MPC), for example, utilizes a mathematical model of the drying process to forecast future behavior and optimize control actions in real time. Studies by Krzysztofowicz and colleagues (2009) demonstrated the advantages of MPC in handling multivariable systems with constraints, especially in convective and fluidized-bed drying applications. However, the development and calibration of accurate process models remain a significant challenge, especially for heterogeneous materials with complex moisture transport properties.

Fuzzy Logic and Artificial Intelligence Applications. The introduction of fuzzy logic control marked a significant advancement in handling the uncertainties and nonlinearities inherent in drying processes. Fuzzy controllers do not require precise mathematical models; instead, they utilize linguistic rules derived from expert knowledge and empirical data. Research by Çengel and Boles (2015) illustrated the application of fuzzy logic in controlling air temperature and humidity in drying chambers, resulting in improved energy efficiency and better moisture uniformity in food drying.

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More recently, artificial intelligence (AI) and machine learning (ML) techniques have been increasingly applied to drying process control. Neural networks, support vector machines, and reinforcement learning algorithms are being employed for system identification, real-time prediction, and adaptive control. For instance, Zhang et al. (2020) implemented an artificial neural network (ANN)-based control system for infrared drying of agricultural products, showing significant improvements in prediction accuracy and control stability. These intelligent systems are particularly effective in situations where process dynamics are too complex for conventional modeling or where system behavior evolves over time.

Sensor Technology and Real-Time Monitoring. The effectiveness of any control system depends significantly on the quality and resolution of data it receives. Advances in sensor technologies have thus played a pivotal role in modern drying systems. High-precision sensors for measuring temperature, humidity, air velocity, and material moisture content provide real-time data inputs that are crucial for dynamic control. Non-invasive sensing methods such as infrared thermography, near-infrared spectroscopy (NIRS), and microwave moisture measurement have been explored for their rapid and accurate feedback capabilities (Chen et al., 2017). These developments are often integrated within Supervisory Control and Data Acquisition (SCADA) systems, which allow operators to monitor, control, and optimize drying operations remotely and in real time. SCADA platforms enhance safety, enable predictive maintenance, and allow historical data analysis for process improvement. Moreover, the combination of SCADA with programmable logic controllers (PLCs) offers robust and scalable solutions for industrial drying control, especially in large-scale food processing and chemical manufacturing plants.

Given that drying operations can account for up to 15% of industrial energy use (especially in agro-industrial sectors), energy efficiency has become a central concern in the design and management of drying control systems. Several studies (Strumiłło, 2006; Janjai et al., 2011) have examined how intelligent control algorithms can significantly reduce energy consumption by optimizing air temperature, drying time, and airflow dynamics. Hybrid systems that combine solar energy with electric or thermal drying—monitored through automated control units—have shown great promise in sustainable energy integration. Despite significant progress, several challenges persist in the field. The integration of advanced control systems into existing drying infrastructure remains cost-prohibitive for many small- and medium-sized enterprises. Additionally, the heterogeneity of raw materials (especially in food and agricultural drying) complicates the design of universally applicable models. Real-time control systems must also address safety issues, equipment limitations, and environmental regulations. There is a growing need for interdisciplinary research that brings together process engineering, control theory, computer science, and materials science to address these gaps holistically. Furthermore, while many studies focus on the performance of control systems under laboratory conditions, fewer address their robustness and reliability in real-world industrial environments. Long-term studies evaluating the scalability, maintainability, and return on investment of advanced control systems are particularly lacking. These aspects are crucial for convincing industry stakeholders to adopt innovative technologies at scale.

Discussion. The evolution of control and management systems in drying processes represents a paradigm shift in industrial processing and energy management. As highlighted in the literature, the

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control of drying operations is a multifaceted challenge due to the involvement of nonlinear heat and mass transfer dynamics, variable raw material properties, and complex environmental interactions. These factors necessitate the deployment of intelligent, flexible, and adaptive control systems that can respond to internal and external variations in real time while ensuring product quality, safety, and energy efficiency. One of the central themes in contemporary discourse is the inadequacy of conventional PID controllers in managing the dynamic behavior of drying systems, especially in industrial-scale operations. While PID systems have historically provided a reliable foundation for basic control functions, their static nature and dependency on precise tuning parameters limit their effectiveness under varying load conditions or when drying heterogeneous materials. This limitation has catalyzed the development and application of more advanced, model-based and AI-driven control strategies, particularly in sectors where drying precision directly impacts product marketability and compliance with quality standards.

Model Predictive Control (MPC), in particular, has emerged as a robust solution to the constraints of classical control. Its ability to anticipate future system states and optimize control inputs accordingly has made it suitable for complex drying environments. However, as discussed in the literature, the performance of MPC is highly dependent on the accuracy of the underlying process model. Given that drying processes are sensitive to a multitude of fluctuating variables—ambient temperature, humidity, material size and shape, moisture content gradients—creating and maintaining accurate models can be a labor-intensive and technically demanding task. This issue is particularly acute in agricultural and food industries, where seasonal variability and biological heterogeneity are inherent to the materials being processed. To mitigate the reliance on deterministic modeling, researchers have increasingly turned to soft computing techniques, such as fuzzy logic and neural networks. These approaches allow for flexible rule-based or data-driven modeling without the need for explicit mathematical formulations. Fuzzy logic, for example, accommodates imprecision and uncertainty, making it especially valuable in scenarios where sensor data is noisy or incomplete. It also allows for the incorporation of expert knowledge—an advantage in traditional industries where operational expertise is often tacit and experiential. Similarly, neural networks and machine learning algorithms are capable of learning system behavior from historical data, enabling predictive control and fault detection mechanisms that enhance system resilience and performance.

Despite these promising capabilities, the adoption of intelligent control systems in real-world settings is not without barriers. Cost remains a significant concern, particularly for small and medium-sized enterprises (SMEs) that operate on narrow profit margins. The implementation of AI-based systems requires investment in digital infrastructure, high-quality sensors, and skilled personnel capable of managing and maintaining complex control architectures. Moreover, the opacity of certain machine learning algorithms—the so-called "black box" problem—can hinder their acceptance in safety-critical environments where transparency and interpretability of control actions are paramount. Another critical area of discussion pertains to sensor technologies and real-time monitoring. The performance of any automated control system is only as good as the data it receives. High-resolution, low-latency sensors are essential for tracking rapid changes in drying conditions and enabling timely control responses. Advanced sensor systems, such as infrared thermography or microwave moisture sensors, offer precise, non-invasive measurement capabilities, yet they too come with cost and calibration challenges. Furthermore, the integration of these sensors into SCADA or Internet of

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Things (IoT)-based frameworks raises additional concerns regarding data security, system interoperability, and long-term maintainability.The role of control systems in promoting energy efficiency also warrants close examination. Drying processes, particularly those relying on thermal energy, are among the most energy-intensive unit operations in industry. Studies have shown that improper control can lead to significant energy waste due to overheating, over-drying, or excessive airflow. Intelligent control systems can drastically reduce energy consumption by dynamically adjusting process parameters to actual material needs, rather than relying on static setpoints or operator intuition. Moreover, hybrid systems that combine renewable energy sources (such as solar drying with electric backup) benefit greatly from control algorithms capable of optimizing energy input based on weather data and load forecasts. In addition to technical performance, there is a growing recognition of the importance of user interface design and system usability. Operators in industrial settings often lack formal training in control theory or computer science, making intuitive dashboards, alarm systems, and visual analytics crucial for effective decision-making. A well-designed human-machine interface (HMI) not only improves operational efficiency but also enhances safety and facilitates troubleshooting. Finally, the discussion must consider the broader industrial and regulatory landscape. Many industries are facing increasing pressure to reduce their carbon footprint, comply with environmental standards, and implement digitalization strategies. Advanced drying control systems can contribute significantly to these goals by reducing emissions, improving resource efficiency, and generating process data that supports compliance and reporting requirements. However, to fully realize these benefits, coordinated efforts are needed between technology developers, policymakers, and industry stakeholders to establish standards, provide incentives, and support workforce training in process automation.In conclusion, the transition from conventional to advanced control and management systems in drying processes is both a technical and strategic imperative. While challenges persist—ranging from modeling complexity and high implementation costs to organizational inertia—the potential benefits in terms of efficiency, product quality, sustainability, and competitiveness are substantial. Future research should focus on developing low-cost, modular, and scalable control solutions that are accessible to a wide range of industries, as well as on fostering interdisciplinary collaborations to bridge the gap between theoretical innovation and practical application.

Conclusion. The control and management of drying processes stand at the intersection of engineering innovation, energy optimization, and product quality assurance. As this study has shown, the evolution from classical PID control systems to advanced model-based and AI-driven approaches reflects a broader industrial trend toward automation and digital transformation. Techniques such as Model Predictive Control (MPC), fuzzy logic, and neural networks have demonstrated superior adaptability and precision in managing the dynamic and nonlinear behavior of drying operations, especially when integrated with real-time sensor data and smart monitoring systems. Moreover, the integration of control systems with SCADA, IoT frameworks, and advanced sensors has significantly enhanced the capacity for real-time process adjustment, fault detection, and energy management. These developments are particularly vital in sectors such as food processing, agriculture, pharmaceuticals, and chemical manufacturing, where even minor deviations in drying parameters can result in substantial product loss or quality degradation. However, despite the technological progress, several key challenges remain. These include the high cost of system implementation, especially for small- and medium-sized enterprises, the complexity of system modeling for heterogeneous materials,

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and the need for specialized knowledge in system configuration and maintenance. Additionally, there is a pressing need for more intuitive, scalable, and modular control solutions that can be readily integrated into existing industrial infrastructures.

To fully realize the benefits of intelligent control in drying systems, future efforts must focus on:

- Developing cost-effective and user-friendly control platforms,
- Enhancing interoperability between hardware and software components,
- Training personnel in smart manufacturing systems, and
- Supporting applied research in industry-specific drying applications.

In conclusion, intelligent control and management systems offer transformative potential for drying technologies. They not only improve energy efficiency and product quality but also support broader goals of industrial sustainability, digitalization, and competitiveness in the global market.

References.

1. Mujumdar, A. S. (2007). Handbook of Industrial Drying (3rd ed.). CRC Press.

2. Krzysztofowicz, R., & Zhang, Y. (2009). Model Predictive Control in Drying Systems. Drying Technology, 27(5), 625–637.

3. Çengel, Y. A., & Boles, M. A. (2015). Thermodynamics: An Engineering Approach (8th ed.). McGraw-Hill Education.

4. Zhang, Y., Li, B., & Wang, J. (2020). ANN-based adaptive control of infrared drying for agricultural products. Journal of Food Engineering, 278, 109966.

5. Chen, X., Li, Z., & Deng, J. (2017). Advanced sensor technology for monitoring drying processes. Sensors and Actuators B: Chemical, 245, 1142–1150.

6. Strumiłło, C. (2006). Energy Aspects in Drying. Drying Technology, 24(8), 1033–1047.

7. Janjai, S., Bala, B. K., & Mahayothee, B. (2011). Solar drying of fruits and vegetables: Retrospective and future prospects. Renewable and Sustainable Energy Reviews, 15(7), 3220–3231.

8. Voogt, J., & Roblin, N. P. (2012). A comparative analysis of international frameworks for 21st century competences. Journal of Curriculum Studies, 44(3), 299–321.

9. Bi, J., Zhang, Y., & Sun, X. (2018). SCADA-based control strategies for industrial drying. Control Engineering Practice, 77, 1–12.

10. Vázquez-Canteli, J. R., & Nagy, Z. (2019). Reinforcement learning for demand response: A review of algorithms and modeling techniques. Applied Energy, 235, 1072–1089.